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A PROBABILISTIC ANALYSIS OF ISLANDING EFFECTS IN A MODELED DISTRIBUTION SYSTEM WITH RENEWABLE RESOURCES

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ABSTRACT

For this research, an investigation was undertaken regarding the inclusion of renewable resources into the distribution system. This incorporated the increasing prevalence of solar and wind resources, as well as the development of islanding capabilities within distribution systems.

A model of an actual distribution system was modified to include both solar and wind generation at the end of a feeder, which was also given the capability of islanding. Backup generation was also added to this segment of the system to ensure the reliability of the operation of the renewable resources. This model system was investigated in two different avenues, probability analysis and transient analysis, which were then experimentally combined into a hybrid analysis.

In the probability analysis, the practice of using probability density functions to describe the behavior of wind and solar phenomena was utilized in conjunction with real-world weather data. This provided a basis for this research to draw real conclusions regarding the adequacy of renewable resources for different portions of the day, as well as realistic estimations of resource contributions. Additionally, alternative methods for investigating the solar resource were analyzed to provide more a more useful approach than the more complex schemes currently being utilized. Lastly, examples of probability analysis providing more accurate understanding than basic analyses of renewable resources were demonstrated.

For the transient analyses, the system model was simulated for various scenarios in the PSCAD environment. The effects of different levels of generation along with the

switching operations associated with islands were explored. This provided a basis to understand some of the effects that may be anticipated by the addition of renewable resources within the distribution system. Not only was this investigated for voltage and current levels, but also for the power generation levels of the renewable resources themselves.

Finally, these two distinctive areas of research were combined to experimentally provide a comprehensive view of such systems. This provided various avenues in which to present original views of the system. Among these included methods of breaking the system behavior down along lines of generation levels as well as time-of-day progression. Additionally, a means of predictive analysis was explored using the combinational methodology, with results being provided by the historic data used for the probability analysis.

DEDICATION

This manuscript is dedicated soli Deo gloria.

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CHAPTER ONE

INTRODUCTION

1.1 Renewable Energy

In an increasingly competitive age for resources that can be converted into the energy necessary for modern society, finite resources such as coal and oil are beginning to lose their desirability as a means of energy generation. What has attracted attention is the concept of "renewable resources," or resources which can be replenished or are available over the indefinite future. According to the Department of Energy, renewable resources are those resources that "…produce sustainable, clean energy from sources such as the sun, the wind, plants, and water" [1]. These resources have a profile that is generally cleaner than their fossil-fuel counterparts, and are available in virtually every geographic region.

Traditionally, renewable resources have only contributed a small amount to the generation portfolio for the developed world, but there are several motivations for their inclusion in the modern grid. First of all, renewable resources have the quality of no fuel costs, therefore if the start-up capital required to construct renewable generation becomes competitive with traditional generation, economically these resources become an attractive addition to a utility's generation fleet. Additionally, the public sector has several reasons to encourage the adoption of renewable resources such as the desire for national energy independence and environmental concerns. Reflecting this, nearly one-third of the generation installed in the United States from 2008 to 2012 was the renewable energy of wind farms [2], and this pattern was also mimicked by the industrialized nations of the EU such as Germany and the U.K. The private sector also has reasons for exploring renewable resources, among these being the relatively greater flexibility in installing renewable generation due to environmental regulations, as well as the entrepreneurial opportunity of a developing technological field.

Although the field of renewable resources is quite broad, the two methods of extracting power from renewables that are currently experiencing the most development are wind turbines and photovoltaic panels. Wind turbines are modern versions of the windmill that have been popular throughout history, from the antiquated windmills used to reclaim Dutch lowlands from the ocean to the utilitarian versions used by farmers to draw irrigation for crops. Modern wind turbines are undertakings of great scale, as they can reach heights of 100 meters and rotor diameters of 150 meters, which is greater than the length of an entire football field [3].

In addition to the advances made in harnessing power from wind, great emphasis is being placed into the development of claiming power from solar energy as well. Modern solar technology is the advancement of the near-ubiquitous photovoltaic cell technology found in devices from calculators to outdoor lamps to emergency radios. In this case, the improved manufacture of photovoltaic cells has increased their power production, and they can be readily installed on buildings or in locations where traditional generation placement is impractical. This power can then be collectively gathered and controlled by electronic controls and connected to the grid via inverter technology. By understanding these two forms of generation, the nature of the future grid as a whole can begin to be understood.

1.2 Wind Energy Production

Wind is universally regarded for its great power, from tornadoes and hurricanes to the mild breezes mills have used for grinding grain throughout history. To harness the power of the wind has been a dream of mankind for millennia, and has been accomplished in some small ways. However, modern ambitions have even higher aims for harnessing the power of the wind, and aspire to use it to drive the energy production of the twenty-first century forward.

The development of wind power technology in modern applications has closely followed the classical method of power extraction from the wind, the wind mill. Today's power producing wind mills are called wind turbines, and their development has been fueled by what is necessary to accomplish the efficient extraction of power from the wind. Modern development of wind turbine technology began in earnest in the 1970's and helped to establish the wind turbine into a viable means of energy production [4]. Noticeable changes in the wind turbines from the mechanical systems used previously were the great sizes of modern turbines, which allow access to greater wind speeds, and the omission of many of the blades used previously. By utilizing only three blades, and controlling their pitch precisely, the modern turbine can extract a great deal of power while at the same time smoothing out many of the fluctuations associated with wind. These adaptations are necessary to address the nature of wind, which must be understood in order to maximize the efficiency of the resource.

Wind can be characterized as a stochastic process, which is not truly random but has randomized patterns and fluctuations that make precise prediction impossible. The unpredictability of wind is universally understood [5], but it can be interesting to note that wind behavior changes noticeably throughout different regions. Note the following histogram (plot of occurences of an event) for wind speeds throughout a year in a coastal region, which shows a definite concentration of wind speeds around a specific value.

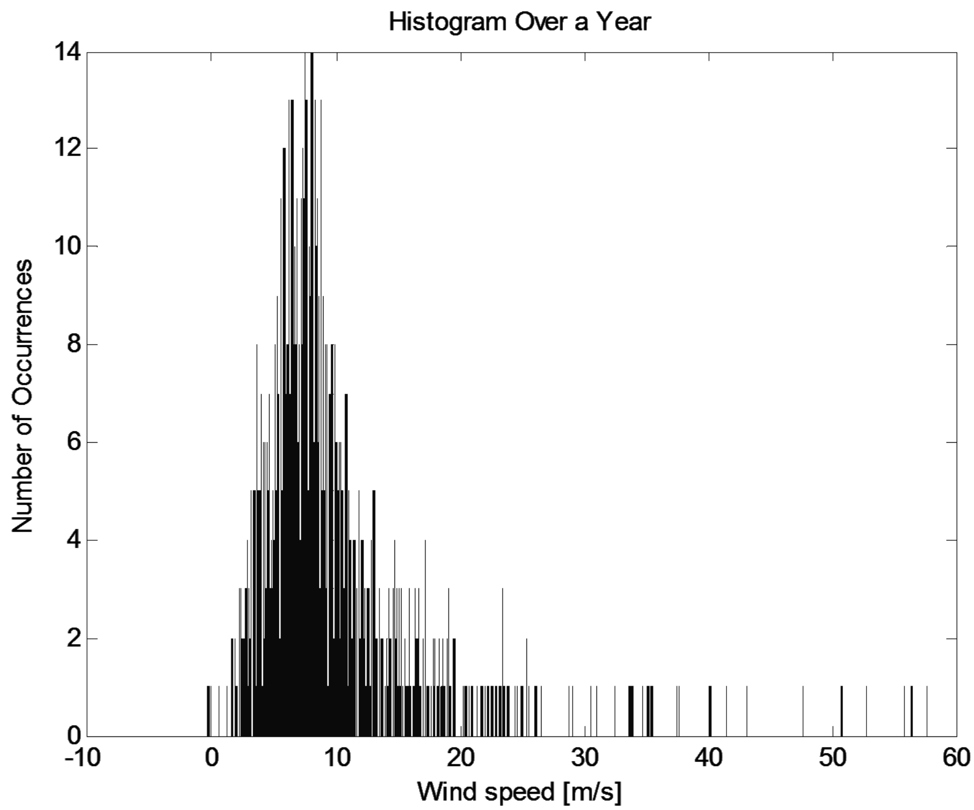

Figure 1.1: Wind Velocity Histogram Over a Calendar Year

Although this is not characteristic of every wind profile for every region, several basic premises about the nature of wind can be gleaned. First, although wind does have a large range of potential values, a definite concentration can naturally occur around certain values. This then implies that although wind cannot be determined from minute to minute, or even hour-to-hour, it can statistically be characterized in a general sense over a long period such as a year. Additionally, the wind shows a characteristic that resembles in some ways a normal distribution, which means that it can begin to be characterized by statistical means, as many natural processes have Gaussian properties. These characteristics of wind have led to the development of technology that is specific to use for wind turbines.

With regards to the electrical design, wind turbine technology has developed a fairly unique application of the induction generator that is known as the doubly-fed induction generator, or DFIG. In a conventional induction generator, an electrical signal is injected into the stator of the machine, which replicates that magnets that are found within a synchronous generator. This allows an induction generator to be run at different speeds while still producing the proper frequency output of the system. This is then taken a step farther in the DFIG, as an electrical signal is injected into both the rotor and stator of the machine, which allows for the dynamic decoupling of machine speed and system frequency. This is desirable for wind turbines, as the minor fluctuations in wind can be compensated for electrically to produce a steady frequency, aiding in the stable operation of the turbine. Relative advantages and disadvantages of this approach are [6]:

- Stable frequency
- Electrical adaptation to mechanical input changes
- System frequency maintained over a range of speeds
- Reactive power injection required for excitation
- Requires grid connection or external support

With all of the developments made in extracting power from wind, the future of power systems will undoubtedly incorporate wind generation. This has been an ongoing development of the means of converting wind to usable energy, and has progressed into a state-of-the-art industry. The nature of wind itself has been the limiting factor of wind generation, but by understanding the nature of wind, this can influence its technological development to promote greater efficiencies and utility. Useful technology has been established in the field of wind generation such as the DFIG, which provides a stable platform to begin incorporating wind generation. In all, wind is a plentiful and clean resource that can be readily integrated into the grid with more confidence as its behavior and technology becomes more widely understood.

1.3 Solar Energy Production

Solar power generation is one of the most advantageous forms of clean and renewable energy, with numerous possibilities for obtaining the energy. The sun is the driver behind most of the natural weather events on the earth, including wind, storms, hurricanes, and the heating of the planet. Therefore, in an indirect way, taking power from wind is only indirectly taking it from the sun. Thus, it is desirable to directly obtain power from solar radiation directly, in hopes of achieving the greatest amount of power generation possible. Much like wind generation development, the nature of the solar resource has dictated how the technology of solar generation has been accommodated to specifically gather the resource.

Solar energy generation has had a more diverse development than that of the wind, with different forms being used throughout history. One of the most basic forms of energy production from the sun is not so much energy generation as energy replacement in the form of using solar radiation to heat water, thereby reducing the energy demand for heated water. This solar heating is still found in many rural areas today. Another alternative form of energy production is to use mirrors to reflect a large amount of the sun's rays onto a concentrated area, thus creating enough heat to boil water or some other substance which can then power a conventional generator [7]. However, the most currently researched form of solar energy production is in the form of photovoltaic cells, which have been in use for years for electronic devices such as calculators. From there, they were explored for their use in being able to generate electricity in areas without access to grid technology and where the installation of something as large as a wind turbine would have been prohibitive. Now, they are being investigated and used on a large scale as a means of power production for the electrical grid.

Although the solar output received on any given day is considered to be stochastic like wind, in reality the two different resources have very different behaviors. Solar output is more predictable in that the driver of the solar resource, the sun, is predictable as to its position and angle. The variations then come from the atmospheric conditions which then modify this radiation to the earth's surface. In viewing this as a histogram the same way as the wind, this shows that the solar irradiance is more uniformly distributed than that of wind, but has a definite decrease towards the maximum potential value.

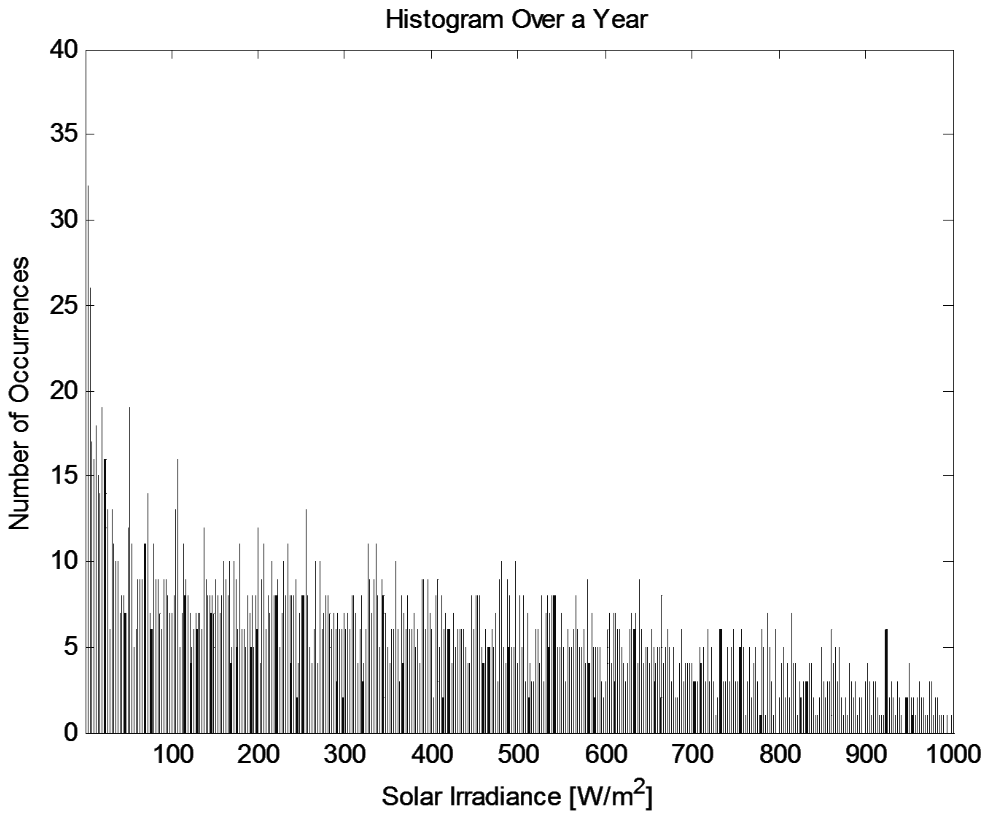

Figure 1.2: Solar Energy Histogram Over a Calendar Year

Although this may seem to be more “random” and unstable than wind, solar radiation has predictable factors such cloud cover that contribute to the availability of the resource that make solar irradiance more predictable than wind [8]. One final aspect about the nature of wind that has made it a very desirable addition to the generation portfolio is its abundance during peak demand times, and thus it carries a high value of replacement generation. The nature of solar irradiance then, while still a renewable resource, differs quite a bit from that of wind.

Photovoltaic technology greatly differs from almost every other form of power electrical grid generation, as it is an inherently DC process that is incorporated into an AC grid. This comes from the fact that solar panels work by inducing electrons to move between layers of doped silicon, which produces a DC current. The technology is then enhanced with what is known as maximum power point tracking, which regulates the voltage levels of the solar panel that change with differing levels of irradiance to correlate with the current that produces the greatest power output. Additionally, the panels are often put on motorized arrays that keep the panels on an angle perpendicular to the sun to receive the greatest amount of solar radiation [9]. However, the most notable technological difference for solar generation is the necessity of invertors to transform the DC electricity into AC, which through electronic controls then reconstructs an approximation of a sine wave signal. Relative advantages and disadvantages of the technology associated with solar generation are:

- Electronic control that provides a non-dynamic, stable output
- Scalabilty, allowing for placement in strategic locations
- DC output useful for battery storage
- Limited output current, making fault detection more difficult
- Harmonics injected from inverters lower power quality

Solar generation in the form of photovoltaic technology is more recent than that of wind turbines, but offers many advantages for inclusion in the future development of the grid. Directly gleaning energy from the sun opens a form of generation that is one of the most promising forms of clean and renewable generation. Additionally, solar's stable nature and on-peak time of generation then makes solar generation an economically attractive form of generation. If the technological challenges of inverters and electronic controls are met, it then becomes a truly viable means of full-scale power generation.

With its scalable nature, this has then led to solar generation being one of the most explored forms of renewable energy for renewable energy production.

1.4 Renewable Resources' Impact on the Grid

The inclusion of renewable resources into a grid that has been fully developed around highly stable synchronous generation and centralized distribution will necessarily have an impact. The opportunity then is to not only make renewable resources acceptable for grid integration, but also make use of them for enhancing the grid. The impact of renewables on the grid can be broken down into three key areas regarding distributed generation, renewable technology, and the uncertainty associated with natural phenomena.

One of the different ways that renewable resources will be integrated into the grid will be distributed generation. Distributed generation differs from classical power grid generation in that it is decentralized and located in sub-transmission systems. Although localized distributed generation has been explored with conventional generation in order to create greater grid flexibility, the rise of renewable generation has accelerated this greatly. This comes from the fact that many renewable projects are small-scale endeavors initiated by third parties. An example of this is the purchase of small solar arrays that homeowners place on their roofs to lower their electricity costs [10]. However, this increased flexibility and decentralization of the sources of generation has drawbacks as well. By locating the generation in the distribution subsystem, any power transmitted significant distances from the source will result in greater power losses. Additionally, this raises safety concerns as power can feed back through lines that were once radial, potentially endangering line crews performing maintenance. By changing the location of the generation, the dynamics of the grid must necessarily change.

Not only do changes in the generation location impact the grid, but also the changes in the generation technology affect the grid. In the case of solar generation, this derives from the electronic control mentioned before. One of the issues of having a source that is only able to output rated current, regardless of voltage levels, is that traditional means of fault protection which rely on current levels will have difficulty detecting system faults [11]. Additionally, the inclusion of inverter technology for the panels introduces harmonics into the system, which increase losses and introduce negative sequence current into the grid. Typically, these harmonics come from the load, and having them come from the generation as well could have adverse effects. Solar technology is not the only renewable resource that will affect the grid, as wind generation has been installed in much greater amounts than solar. The wind generation will affect the grid main in the areas of requiring increasing reactive power support, as well as system dispatch. The reactive power that wind turbines draw have been largely provided by grid side generation, but as their penetration increases, conventional generators may not be sufficient to provide enough generation to support the reactive power required. Therefore, in large installations, generators are sometimes added specifically to provide reactive power, and are known as synchronous condensers [9]. In the dealing with the changes in technology with renewable resources, the ways in which the grid is operated, such as protection and VAR support, will change as well.

Even though the changes in technology are a significant challenge to be met, the greatest obstacle associated with incorporating renewable resources into the electrical grid comes from the uncertainty associated with their power output. The grid has developed into a system that relies on regular power dispatches in order to promote economic operation and dispatch, as well as system stability [12]. By including a resource that has an indeterminate amount of power generation, other power generators must be able to withstand a larger dynamic range of power demand. This can have negative impacts on economical operation and system operation. Additionally, the large swings that can accompany the unplanned change in power generation can create instability in the system, which has led to voltage collapse [13]. To mitigate these situations, different solutions have been explored, but the shared aim of them is to reduce the uncertainty associated with renewables [14]. If the uncertainty to renewable generation can be effectively mitigated, renewable resources will quickly gain acceptance.

The location impact of decentralized distributed generation, the technological challenges of unconventional generation, and uncertainty in resource output all shape the impact of these resources on the grid. Distributed generation will change the flow of power within the system, as well as the system operations needed to maintain optimal operating conditions. The technology associated with both solar and wind have unique characteristics which may require additional accommodations, such as filters for solar inverters and synchronous condensers for wind turbines. Most importantly, the uncertainty in natural phenomena will affect the entire operation of the grid, and will become increasingly important as renewables continue to grow as a percentage of the generation portfolio. In summary, there are numerous advantages and disadvantages to renewable generation:

Advantages:

- Distributed generation adds generation without significant transmission costs
- Distributed generation can provide greater system flexibility and reliability
- Solar generation can be implemented on small scales
- Renewable generation has no fuel costs and no emissions

Disadvantages:

- Complex dispatch and higher costs can accompany distributed generation
- Safety risks for maintenance crews are increased by decentralizing control
- Solar generation can affect the protection for many power systems
- DFIG technology requires constant reactive support and electronic control
- Uncertainty in the grid generation can lead to uneconomical operation

1.5 Islanding Operations and Renewable Generation

With the advancements of the placement and technology associated with renewable technology and grid modernization, an additional topic that has received much attention is that of islanding. The concept of islanding, or removal of a section of the grid to operate on its own, presents operational flexibility when dealing with distributed generation. If islanding is properly understood and implemented, the grid can take the next step in modernization. Once islanding is understood, its specific operations and its connections to renewable resources can be explored.

To understand islanding, it must understood what is meant. Generally speaking, islanding is any situation where a section of the grid is disconnected and is still capable of balancing generation and load. This then can be further characterized as intentional and unintentional islanding. Intentional islanding is a pre-planned operation carried out by a utility or operator and unintentional islanding comes from a system reaction to a disturbance such as a fault [15]. Therefore, by definition an island must have an internal source of distributed generation, and an example of an island configuration can be seen in the figure below.

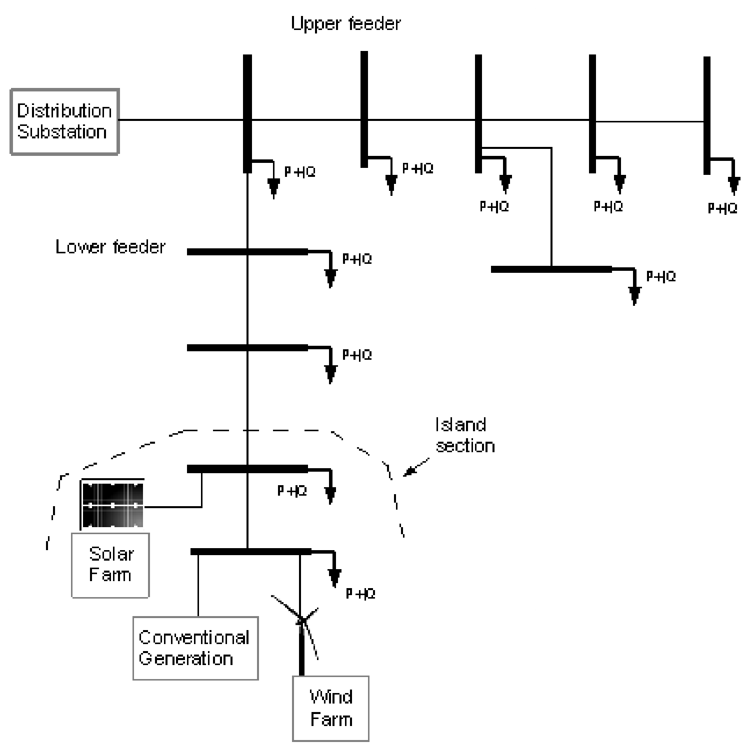

Figure 1.3: Example of an Island in a Distribution System

As seen from the definitions of islanding, there are different avenues through which it occurs, resulting in different possibilities for the operation of islands. These possibilities all stem from different advantages that islands can provide utilities. Some of the potential benefits of islanding are:

- Better economical operation under certain conditions
- Ability to shed load from the larger grid without loss of customer power
- Improved reliability and security
- Increased voltage support and regulation
- Potential for greater free market operation

While the operations of the islands hold many potential benefits, there are possible drawbacks as well. If an island is not prepared to be disconnected from the grid correctly, the distributed generation may not be able to support the load, causing voltage collapse and blackouts. Additionally, reclosing an island back into the grid without proper synchronization can lead to instability, and potentially damage the customer load within the island [16]. These considerations for island operation are part of the decision-making process that will have to be made in the future grid.

One of the leading motivations in being able to create islands that are operated in this manner is the growth of renewable resources in the grid. One of the terms that has been used to link islands with renewable resources is "microgrid." A microgrid is a small self-contained system that specifically incorporates renewable resources and the necessary backup generation and communication to reliably and economically operate the system [17]. This type of system has been proposed for institutions that desire to be on the leading edge of grid development. However, by including renewables and distributed generation, microgrid operators must take further steps to ensure that their system remains free of frequency disturbances, instability, loss of generation, and compensates for lack of spinning reserves. Renewable generation in islanding is one of the grid concepts of the future, but it must be approached.

Islanding in the grid will continue to grow as a subject of increased interest as electrical systems become more flexible. Their operations, when properly defined and executed, can help to ensure that more people will receive reliable power, and that utilities and energy providers can increase economical operation. With renewable resources, this islanding concept can then be taken to the level of full-fledged microgrids where the operation of the system falls upon independent operators instead of utilities. With all of these concepts, the potential for improved operation is increased, but is balanced against the challenges that islanding brings as well.

1.6 Thesis Outline

To understand the operating conditions of systems that incorporate renewable resources and islanding, the first step is to create a plausible distribution system that incorporates these elements. This distribution system contains a section that is capable of handling islanding, as well as incorporating both wind and solar renewable resources. This distribution system could be capable of turning on and off the renewable resources at command, as well as having a dispatchable backup conventional generator to back up the renewables. This system, modeled in a medium voltage, provides a platform with which to explore these different concepts.

Many systems that have been created to study the phenomena of islanding and renewable resources assume idealized or static loads and circumstances. However, in the case of distribution systems, the load is non-ideal. Because of this, the study of imbalance will be introduced into the system in order to understand what effects this may have in relation with renewables and islanding. Also in renewable studies, the load is often modeled as a static element, so in order to better understand the correlation of renewables to meeting demand, a dynamic load should be created. Thus the loading effects can be an important piece of an islanding and renewable resource study.

When a system is islanded, the effects of the lines and generation being tripped on and offline will create momentary phenomena that may affect the system. Therefore, it is important for a serious study to also include analysis of the impact on the system to operate during a transient time frame. This way, the ramifications of the different operations may be better understood. This transient study can also have the benefit of better revealing the parameters with which renewable resources should be operated to promote greater economy and reliability. A transient study can reveal further details in understanding microgrid-type systems than a standard type of traditional system.

The study of renewable resources can be executed through many different means, but one of the most promising has been that of probability analysis. These analyses often only focus on energy studies, or being able to adequately meet load over a period of time, but with the proper data and analysis they can reveal a wealth of information about renewable resources in a given area. This research explored some of the applications of probability analysis to renewable resources, and what probability measures best fit the renewables, particularly the solar resource.

The overall key to the study is to link the probability analysis with the transient study, which are two domains of study that do not typically overlap. This combination will serve to create an accurate overall picture of a system that incorporates renewable resources with an islanding capability. The way this is accomplished is to create a diverse set of operating conditions which can be characterized by particular system parameters, and then determining a probability on each scenario. As each scenario then has particular transients associated with it, the transients of the system can then also be given a probability of occurrence.

The outline of this paper will explore these different aspects of research. Chapter 2 will detail the development of the system model and its incorporation of the renewable resources. The differences in the load profiling, such as creating imbalance in the system as well as non-ideal loads, will be discussed in Chapter 3. In Chapter 4, the transient analysis of the system will be presented, detailing the different operations of the systems and their associated effects. Chapter 5 will be the probability analysis of the renewables, and will include a practical exploration of the resources as well as a study of the different possibilities of analyzing the solar resource. After these elements are available to be combined, Chapter 6 will then detail how the probability analysis and transient study can cooperatively create an overall picture of microgrid-type systems. The overall results and conclusions will then be summarized in Chapter 7.

CHAPTER TWO

DEVELOPMENT OF ISLANDED SYSTEM WITH WIND AND SOLAR GENERATION

The first logical step for developing a case study is to create a modeled system for simulation. With this basic model created, the different aspects of the study can be varied individually and studied for their relative affects. With a viable base model of a distribution system, the model can be modified to allow for an islanding situation. With the island set, the portfolio of renewable generation can be determined to best suit the ideal self-supporting generation scenario. The development of this system begins with the basic model of the distribution system, progresses to the creation of the island within the system, and ends with the sizing and placement of the renewable resources. To create a greater understanding of the concepts presented, the definitions of some of the more used concepts in this chapter are:

Base System: A model representation of a realistic distribution system from the given substation, not including the addition of island capability and renewable generation, and idealized to only include modeled lines, buses, and loads.

Islanding Capability: The ability for a section of the system to electrically isolate itself from the rest of the system while maintaining an internal source of generation.

Solar Generation: In this system, the solar generation is an equivalent solar farm that is capable of being connected or disconnected to a particular bus.

Wind Generation: For this study, the wind generation is an equivalent wind farm that is modeled with DFIG controls, and connected to a particular bus within the system.

Backup Generation: The backup generation is not specified as any particular type of conventional generation, but is rather modeled as an adjustable-power source that can be connected or disconnected similar to the renewable generation.

2.1 Development of A Basic Distribution System Model

Before a viable model of a fully integrated microgrid-type system is used for a study, it is most prudent to develop a system model that is acceptable as a simple model for a distribution system. In this case, a realistic model of a distribution system was developed by using a sample distribution system from a mid-size utility, and eliminating buses through the progressive reduction of buses and lines and the creation of equivalent loads. After the buses were reduced and loads concentrated, the final model of the system consisted of 14 buses with 18.2 MW and 9.0 MVAR of load distributed throughout the system. The overall design of the system, which has a substation equivalent being taken by two distinct feeders, can be seen in Appendix A.

The base system finally developed for the study is modeled from a substation and distributed through two feeders. The system voltage is 12.47 kV, and the primary feeders supply eight buses, and the secondary feeders supply six buses. Each bus is connected by a modeled distribution line that includes line parameters to provide a more realistic voltage profile and power flow within the system. This system is modeled in the same manner as IEEE standard systems, which consist of specified loads at buses connected through parameterized lines, but is idealized in that step-down low-voltage transformers, protective relaying, and reclosers are not included within the system model.

In constructing the system, the loads become progressively smaller as they near the far end of the secondary feeders, which is typical for most distribution systems in order to mitigate voltage drop. Additionally, the system as constructed is completely radial in the two feeders, as are most feeders in rural areas. The load is also modeled as a static load, which is condensed as a single bulk load attached to each bus. Therefore, the basic system has unidirectional power flow through the distribution feeders, supplying bulk point loads at every bus.

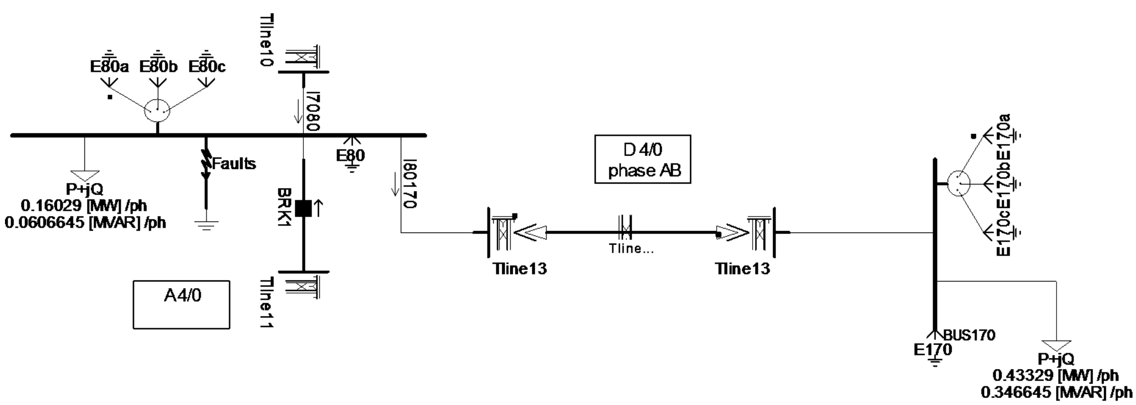

Figure 2.1: Example of Buses, Lines, and Loads

Table 2.1: Load Placement of Original System

Bus #	MW (per phase)	MVAR (per phase)
10	Swing Bus	Swing Bus
20	1.417	0.4367
40	1.248	0.4658
100	0.3791	0.1451
50	0.4875	0.1733
60	0.4323	0.3683
140	n/a	n/a
70	0.6608	0.2253
110	0.2881	0.1105
160	0.4506	0.1516
80	0.1603	0.0607
170	0.4333	0.3466
180	0.7431	0.2643
200	0.65	0.2578

2.2 Determination of Island Location and Parameters

The location of the placement of the island within the grid was the first step that had to be undertaken to modify the system for simulations. In this case, a natural location for system islanding can be seen as the bottom two buses of the system feeder, buses 180 and 200. One of the first aspects to be noticed about this feeder is that the loads are not as light as the loads in the upper feeder, therefore voltage dip could be aided by locating distributed generation in this area. Additionally, locating the distributed generation at the end of a feeder that is not the longest feeder in the system allows the renewable generation to support the load during the non-island mode.

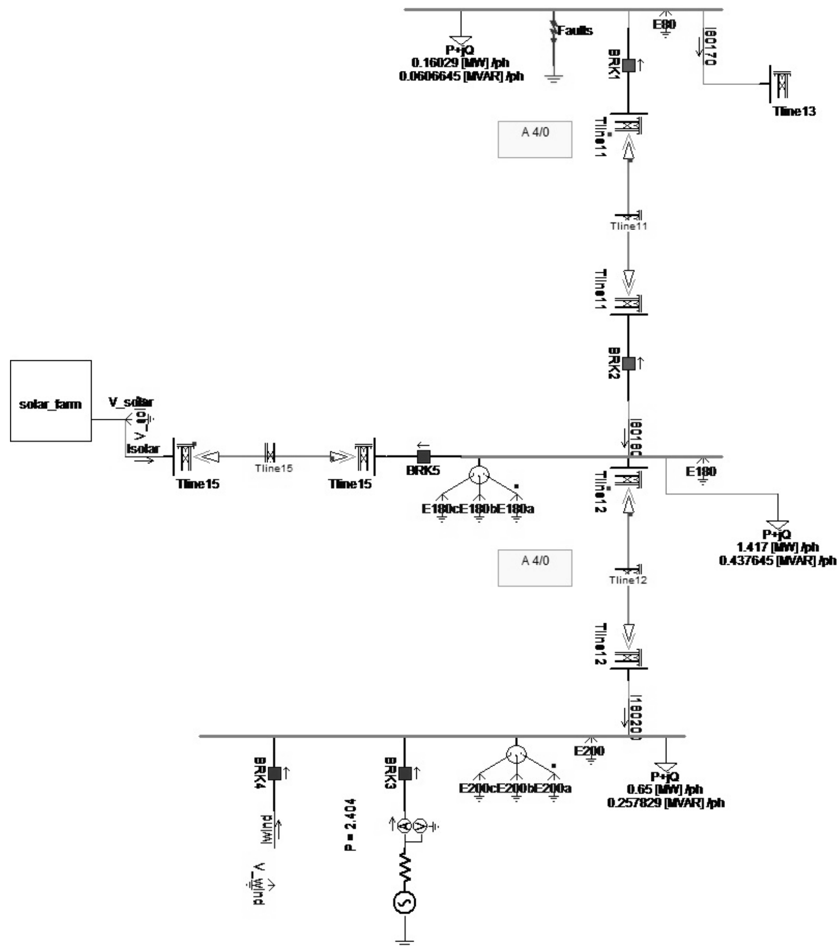

Figure 2.2: An Island System

A change made to the system to fully utilize the islanding capability was to increase the load supported by the island sources. However, it was not desired to change the overall load of the system by simply increasing the load within the island, so part of the island load was exchanged with a load closer to the substation. From the next table, the load at bus 180 was exchanged with that of Bus 20, which gives a heavy loading condition for testing a mix of renewable generation within the island. In all, this gives a combined load of 6.2 MW of load within the island.

Table 2.2: Exchange of Load for Island

Bus #	New MW (per phase)	New MVAR (per phase)
20	0.7431	0.2643
180	1.417	0.4367

Another parameter that needed to be established for the research is under what conditions the islanding operations will occur. Without constantly adequate generation, the grid could suffer a voltage collapse, which would lead to a blackout [12]. If the island is to be a solution that is able to be activated during a situation such as a fault or unforeseen incident, the backup generation must be activated before the islanding occurs to provide assurance of a stable system. However, it is uneconomical to keep the generator active at all times, and thus the generator activation could also be activated at the creation of an island. The final scenario is that the generation will not be able to be activated within the time that it takes to contribute to the island. Therefore, three scenarios can be presented for the basic analysis. The first scenario is that the island is going to be intentionally created, and thus the backup generation will be running before the island is created. The second scenario is that the island is not being intentionally created, but is instead a reaction to a disturbance; thus the generation will be brought online as the island is created. The final scenario is that the backup generation is unable to be brought online before the stability is lost within the island.

Next, the different situations under which the island can be operated must be established. There are essentially two different situations, which are the operation of the island under desired conditions, and operation under a disturbance such as a fault. For the first scenario, the island must be capable of supporting itself. This means that there must be sufficient wind and/or solar irradiance present to fully support the island in conjunction with the backup generation. In the second scenario, that of fault switching, the backup generation and the renewable generation must be capable of operating the island. In these simulations, the bus at which faults will be simulated is the bus closest to the island, making the effects of the fault to the island will be the most severe. The most common fault, which is the single-line to ground fault, and the most severe fault which is the three-phase fault, will be explored. Finally, an islanding situation where there is an island created that quickly reconnects will be explored.

- First Scenario: Intentional Islanding

For the first situation, that is, an intentional islanding, there must be a range of scenarios under which this island is capable of operating, essentially the mix of generating capacities under which the island operates. For intentional islanding, this comes from a three potential conditions: sufficient wind generation, sufficient solar generation, and sufficient wind combined with solar generation.

- Second Scenario: Unintentional Islanding

The second scenario under which the island is a resource is maintenance of the grid under a disturbance. The generation scenarios under which this is able to occur are the same as intentional islanding, but also include the additional cases of completely adequate wind power for the island and completely adequate with wind and solar. This then gives a wider range of possibilities within the generation of the island, and must be controlled accordingly. As was mentioned before, this can create the possibility that there is more power in generation than in load, and the possibility exists that the generation within the island must be reduced. One way this can be accomplished is by switching off the solar generation, the wind generation, or potentially some of the turbines within the wind park. That means besides the aforementioned scenarios of simulation, three more scenarios must be created. The first scenario is that there is too much of a combination of wind and solar generation, but the tripping of the solar generation is sufficient to match generation. The second scenario is that there is too much of a combination of the two, but that the loss of solar is insufficient to create a healthy island, therefore the wind must be switched off. The final scenario is that there is insufficient solar generation to power the island, but the wind generation by itself is still too much for the load within the island. In this case, a step input representing the tripping offline of several of the wind turbines will be implemented within PSCAD to simulate the attempt at load matching.

- Third Scenario: Reconnection to Grid

Finally, the scenarios of reconnection to the grid must be simulated to create a complete picture of the full operations of an island. Like disconnection from the grid, this must be simulated for several scenarios. The first scenarios are the same as intentional islanding, where the backup generation provides the necessary range of generation to supply the island. The next scenarios are the reverse of the specialized scenarios for the generation shedding, where there is sufficiency within the renewable resources to overpower the island. When reconnected to the grid, the three previous scenarios should be investigated in reverse. The solar generation should be energized after connection, the wind generation should be energized after reconnection, and the number of active turbines within the windpark should be adjusted upward in order to gain as much a power out of the wind resource as possible. The final scenario that should be simulated for reconnection to the grid is that of the renewable resource generation becoming inadequate to supply the demand in the island. This can be accomplished much in the same way as the effects of having to reduce the generation are investigated.

2.3 Sizing, Placement, and Parameters of Renewable Resources

One of the areas of uncertainty with renewable resources is the necessary amount of nameplate generation to fulfill the needs of the system. With indeterminate utility factors, even the design of the size of needed generation can be involved. This must be applied to the wind and solar generation, and these ultimately help to determine the necessary size of the backup generation.

As the main driver of the renewable generation used within the islanding, the wind resource is the most important item to be sized, and coordinated with the other resources within the system. Additionally, the control systems and technology used to implement wind turbines are more sensitive to phenomena such as voltage dips and system stability [18]. Since the average island load is approximately 6 MW, the utility factors for wind generation can be used to size the needed wind turbines. The utility factors for wind generation can vary greatly, and differ among the manufacturers as to what each turbine can accomplish, and are ultimately controlled by the atmospheric conditions of the region in which they are placed [19]. A utility factor of 40% was selected for this research, which would be considered a high factor for wind resources, but is justified in light of the consistent wind generated from coastal regions. With this utility factor, a wind farm nameplate rating of 12 MW was selected for two primary reasons. First, with the utility factor of 40%, this would give an average expected output of 4.8 MW, which would provide power to the majority of the loads in the island. This design can be achieved through the installation of 8 wind turbines, each 1.5 MW (a standard industry size) as a small wind farm [20]. This results in an achievable wind production that is much higher than what is needed to sustain the load, but in systems with little or no energy storage, this is necessary in order to provide meaningful reliability in the system [21]. The major source of distributed generation was placed at Bus 200 to give voltage support and reasonable power flow through the system.

In hybrid systems, the sizing of the solar generation in comparison to the wind generation is often quite small [22]. In this case, a theoretical ratio of 10:1 was used for the wind generation to the solar generation. This ratio is based on the nameplate ratings of the generation, therefore with a nominal 12 MW of wind generation, this constitutes a nameplate rating of 1.2 MW for the solar generation. However, the nameplate rating of wind turbines may be much higher than the average output power by the solar panels. Utility factors for solar generation are often quite less than that of renewable wind generation, and typically within the range of 15% to 20%. While this may at first seem to be low, the total amount of solar is limited by a factor that does not affect the wind. Roughly half of the day will never have solar generation. When considering this, solar generation’s utility factor of 20% corresponds to 40% of that of a wind resource. To represent the different possibilities of location that solar generation presents, it was therefore located on Bus 180 to be distinct from the wind resource generation.

With the determination of wind and solar generation, the final piece of necessary generation to maintain system stability is the conventional backup. According to system stability theory, the generation output is dominated by the wind turbine, which has the largest share of the island's generation [12]. That means that there should be a sufficient amount of conventional generation to help mitigate the effects of having such large penetration by the wind turbines, but not enough generation to sustain the island under normal conditions. With these parameters set, a 5 MW limit was selected for the conventional backup generation, which is more than 1 MW less than the power required by the island. As this backup generation had to be included on one of the buses already occupied by renewable generation, it was decided that the most logical placement would be on bus 200 with the wind generation, as many wind farms locate conventional generation nearby for backup purposes.

Table 2.3: Distributed Generation Nameplate Output

Generation	Bus #	Nameplate (MW)
Wind	200	12
Solar	180	1.2
Backup	200	5

With the creation of the basic system, the island, and the renewable generation, a viable model of a distribution system is ready to conduct a study in this area. By starting at the beginning and building a base system and then incorporating the changes, a reliable study can be made. The addition of the island is then a simple process of selecting a suitable area and installing switching capability. Lastly, appropriately sizing the renewable generation includes taking into account the proper mix of generation to best maintain a healthy and operational island.

CHAPTER THREE

LOAD PROFILING IN AN UNBALANCED DISTRIBUTION SYSTEM

3.1 Overview of Need of Different Types of Load Profiling

For many studies that deal with the integration of renewable resources into power systems, only the generation side of the power balance equation is addressed. The other half of the equation, load, is typically held static as it is outside the realm of control for renewable generation. However, to fully understand the impact of renewable distributed generation to the system, the load must be modeled in a more realistic manner as well. This encompasses a long-term load study, as renewable resources change with the seasons, situational studies, which deal with the systemic differences that can occur in realistic loads, and non-static variations such as harmonic loads that can distort signals in a way that is not reflected in typical studies.

Three distinct avenues therefore present themselves for study. The long-term study should reflect the differences between seasons in load profile, as the load dynamics change based on temperature and other seasonal fluctuations. Typical studies assume a static load throughout the entire year and base the adequacy of the renewables on being able to meet the static load. For the second situation of systemic differences, typical studies assume a balanced load valid only for transmission level studies. For distribution level studies, however, this becomes inadequate as the load in lower-voltage systems tends to be unbalanced. For renewable studies load has been typically characterized as a constant P and Q demand. In realistic systems, the load has non-idealities such as harmonic components which may be of greater importance when electronically controlled generation sources generate non-idealities of their own.

To address the first area of question, which is the change of load over the course of the seasons, a dynamic load profile was created that reflected a typical day for each season. A day was defined to consist of several blocks of static load profile, so that the demand more accurately reflected the changes typical of a day of operation. The second situation, where an ideally balanced load profile has been used for previous studies, was corrected through creating an imbalanced profile for the system with the method used by utilities to handle imbalance in the distribution system. Finally, for non-ideal loads, an exploration of harmonics created by machines and their interplay with the electronically controlled voltage was investigated. By changing these aspects of the load, the system and study as a whole are made more robust and realistic to provide a more complete view of how renewable resources can be incorporated into the distribution system.

3.2 Creation of Dynamic Load Profile

As the renewable resources are dependent on time, weather, and seasons, so is the load. Thus for the sake of consistency, the profile of the load over the seasons should be modeled to use in conjunction with the wind and solar resources. In this way, the statistical evaluation of the sufficiency of the renewable resources can be analyzed in a more robust fashion [23]. If the load profile is able to be captured, the changes can be adapted to any size of load that is simulated.

The first decision that must be made for the adaptation of a load profile is the division of the load profile into different times. For this research, the load profile is first of all divided by season, which has a distinct difference in load for each season. Seasonal divisions have been used to delineate effective changes in the behavior of renewable resources, and are a practical starting point for the renewable analysis [10]. Note the below figure, which shows the disparity within the seasons for solar output.

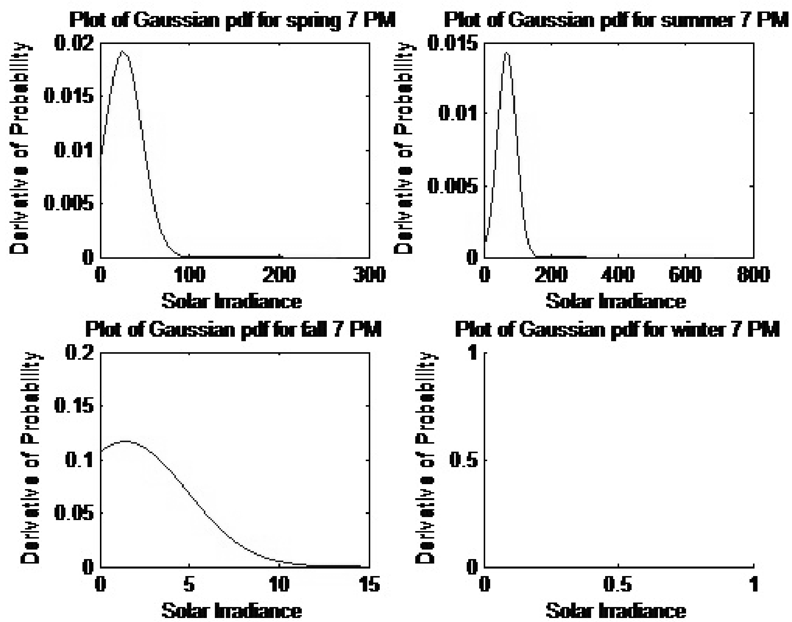

Figure 3.1: Example Seasonal Deviation for Solar Irradiance

A hypothetical day is then constructed for each season using the load profile data for an actual distribution system. This is accomplished by finding the average load for each hour of a day over the three month period, thereby effectively reproducing the load for a typical day for the season. This day is then divided into six distinct four-hour segments of uniform distribution. These blocks were utilized instead of the hour-by-hour profiling to draw more generalized conclusions about the adequacy of renewable generation to match load. For example, this allows the late evening to be compared to afternoon, instead of just midnight to noon. The load profile used for the research consists of the distribution load data from a real utility recorded hourly over the course of an entire year, which yields roughly 8,760 data points from which to extract the load profile. In this way, an adaptive load profile for the area can be created year round in order to provide a more accurate picture of how effectively the renewable resources will be able to meet load demand.

The final aspect of the parameters that must be determined is that of the load levels. The raw data, provided by an area utility, represents a distribution subsystem that contains a maximum of over 400 MW of load, with an average load of around 350 MW. As this is much larger, this is scaled to properly characterize the distribution subsystem that is modeled in PSCAD. This took a small amount of processing, where the maximum and mean values of the real load were found in order to create a profile to use for the modeled distribution system. The mean value of the load was then used for the 6 MW point of the island. This then gives a maximum island load of 7.2 MW, and a minimum of just at 3 MW. In this way, the distributed generation should still have the capacity of always meeting the load requirements, as long as there is a reasonable amount of the renewable resources present.

Given these parameters, a final load scenario was constructed, resulting in a theoretical day profile for each season.

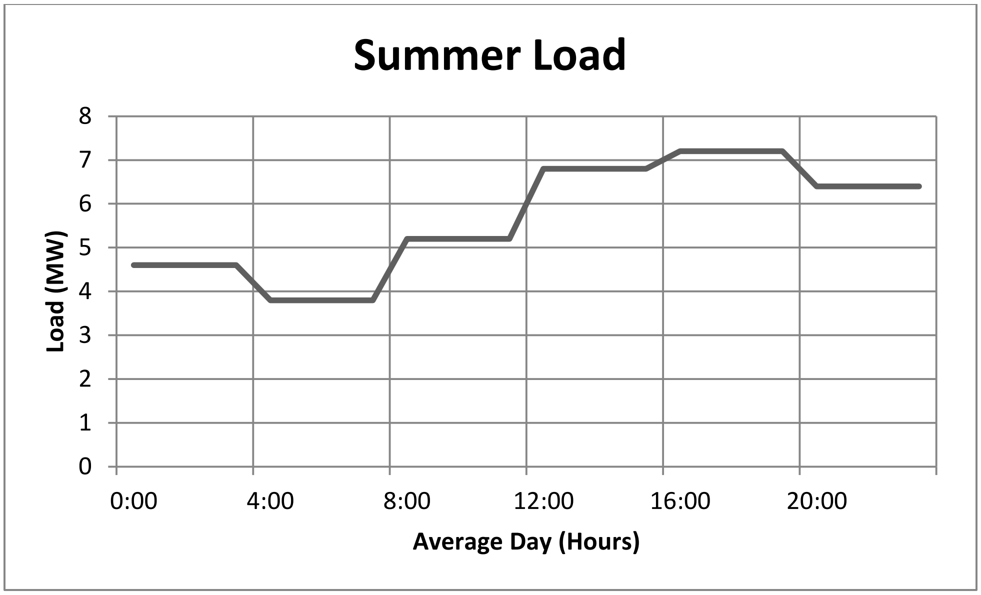

Figure 3.2: Summer Load Profile

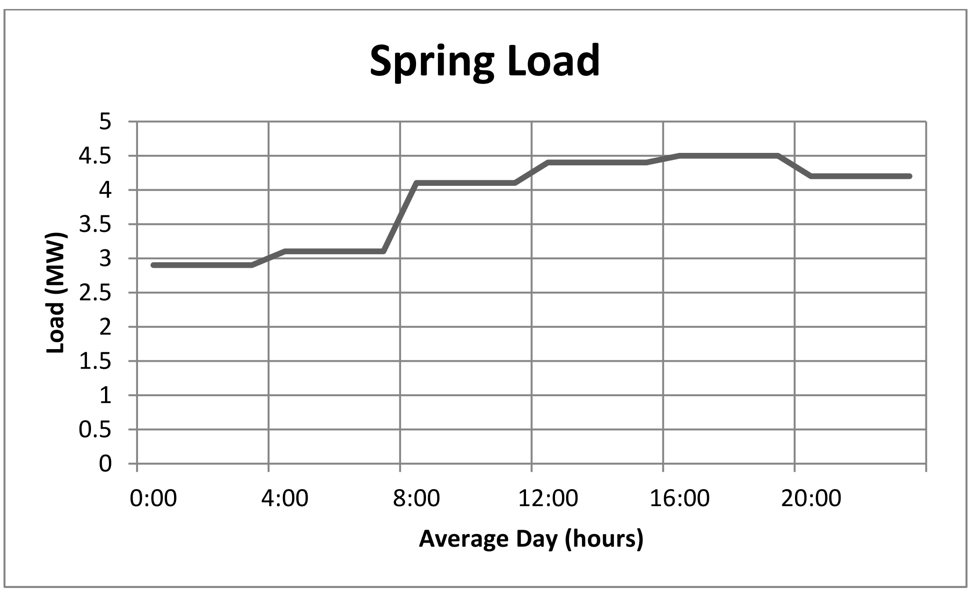

Figure 3.3: Spring Load Profile

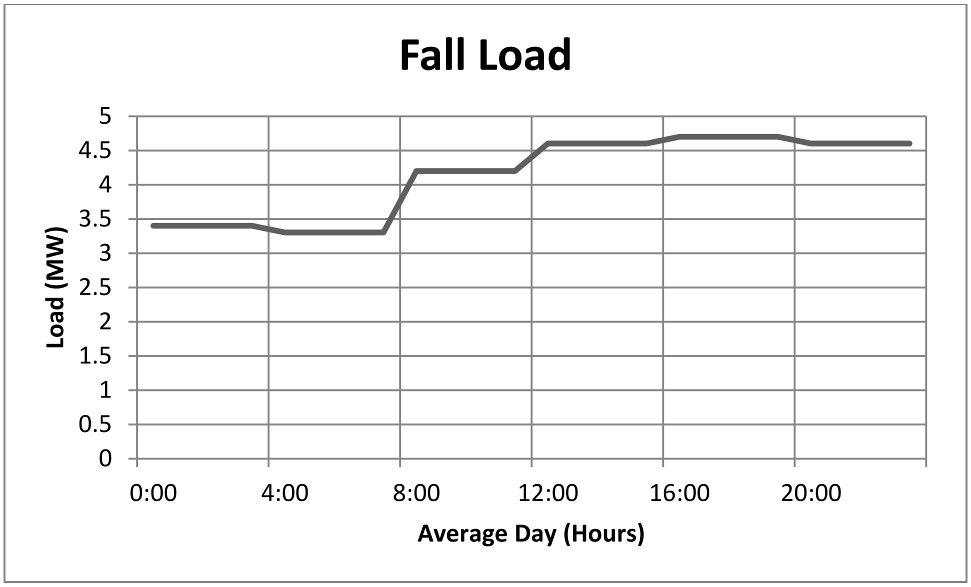

Figure 3.4: Fall Load Profile

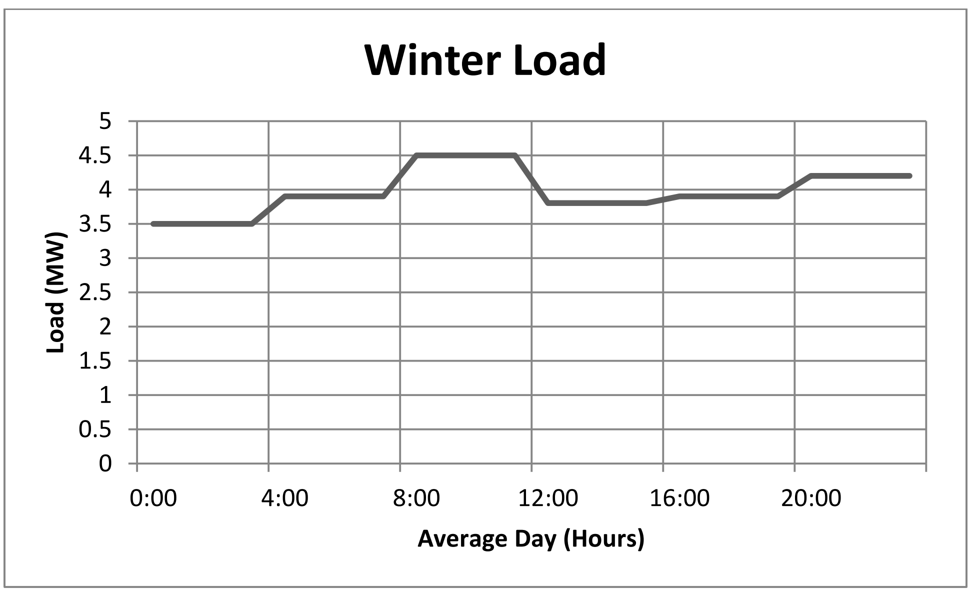

Figure 3.5: Winter Load Profile

By creating a dynamic load profile for each of the seasons, a much more accurate picture can be generated relating renewable generation to matching load. This allows for a greater understanding of the relative worth of renewable resources, as generation has a definite time difference in value. With this data, a clearer understanding of the adequacy of the generation for different periods of the day can emerge and begin to answer some of the basic questions of renewable generation.

3.3 Imbalance in the Load

While the generation from these renewable resources has been carefully studied under balanced conditions, it is critical to understand the implications of unbalanced loads. When dealing with the transmission system, this is often a safe assumption, but in distribution systems balance is often unachievable. What many utilities attempt to achieve is in a sense a balancing of the imbalance, where the most heavily loaded phase is rotated at each bus in order to present an aggregate load to the substation that appears to be mostly balanced. However, from the viewpoint of distributed generation this again leaves an unbalanced load to match, and for islanding, this balance is more difficult to achieve with the limited number of buses. Therefore, a method for the creation of imbalance in the model was investigated, adapted for the islanded, and implemented within the system.

To more accurately model the occurrence of imbalance within the distribution system, the loads at the various buses will be altered to be disproportionate among the three phases. The basic formula used to create the imbalance within the earlier modeled distribution system was

$$Imbalance = \begin{cases} Load(a) = Load(c) \\ Load(b) = 0.3 * Load(a) \end{cases} \tag{3.1}$$

where the total load of the phases is equal to that of the three-phase load previously located at the bus. However, this creates a severely imbalanced overall distribution system, and distribution systems engineers typically attempt to counteract this affect by rotating the imbalance of the phases within the system. Therefore, the phases were rotated to mimic how utilities attempt to lessen the imbalance seen by the primary side of the substation transformer [24].

This imbalance of the load has the problem within the island of creating an imbalance that cannot be rectified simply through rotation. This is due to the fact that the island only contains two buses, and is reflective of the possibility that the load will typically have a more severe imbalance within an island situation. Therefore, an islanding situation will experience more imbalance than a normal system, and this is reflected within the study simulations. The mitigating factor that was used to help the island was the comparison of the size of the loads within the island, and assigning the most heavily loaded phases to strategically balance the load. This serves the same purpose as rotation of phases, but whereas the rotation of phases tries to balance the phases in aggregate, the island's loads are deliberately balanced individually.

With the rotation of phases efficiently determined, next was to strategically balance the load within the island. The imbalance as finally set is seen in the following table:

Table 3.1: Imbalanced Load Within System

Bus #	Phase A Load MW/MVAR	Phase B Load MW/MVAR	Phase C Load MW/MVAR
20	0.2907/0.1035	0.9693/0.3447	0.9693/0.3447
40	1.6278/0.6075	0.4881/0.1821	1.6278/0.6075
100	0.4947/0.1893	0.4947/0.1893	0.1482/0.0567
50	0.1914/0.0678	0.636/0.2259	0.636/.2259
60	0.5652/0.4803	0.1695/0.144	0.5652/0.4803
140	0.8421/0.3222	0.8421/0.3222	0.2526/0.0966
70	0.8619/0.294	0.2586/0.0882	0.8619/0.294
110	0.3759/0.144	0.3759/0.144	0.1128/0.0432
160	0.1764/0.0594	0.5877/0.1977	0.5877/0.1977
80	0.2091/0.0792	0.2091/0.0792	0.0627/0.0237
170	0.5652/0.4521	0.1695/0.1356	0.5652/0.4521
180	0.5544/0.1712	1.8483/0.5709	1.8483/0.5709
200	0.8478/0.3363	0.2544/0.1008	0.8478/0.3363

3.4 Creation of Non-Ideal Load Study

One of the criticisms of electronically controlled renewable generation is that of poor quality and harmonics resulting from the inverters used to create three-phase AC from DC power. This arises from the operation of the inverters, which in many cases are variations of thyristor technology, also known as an SCR, or silicon controlled rectifier. In the operation of this system, the inverters receive an AC-type signal at their gate, which allows them to turn on and off at the time necessary to reconstruct an AC signal. This occurs from an inversion of the basic principle learned within signal analysis, that a rectangular wave can be represented by an infinite sum of appropriate sine waves.

Therefore, the inversion process, which would normally output a rectangular wave if driven in a simply binary form, can actually approximate the output of a sine wave through the addition of many rectangular wave signals. This approximation of a sine wave through the addition of rectangular waves naturally leads to harmonics occurring within the solar generation. However this can often be mitigated through the use of appropriate controls and filters. Within PSCAD, this is accomplished through utilizing a very simple low-pass filter, where a simple inductance is included after the inverters to smooth out the signal.

One of the concerns with solar generation is that it will reduce the overall power quality of the grid and introduce harmonics that may be potentially damaging within the system. However, as a distributed source of generation, it is important to understand the relative weight of the impact that this will have in comparison to the load, which can introduce harmonics of its own. An additional area of study that needs to be investigated is if the harmonics of the generation combine with that of the load to create any unanticipated affects. To accomplish this part of the study, the load will be modeled differently within the island than before. The top bus in the island, which has the heaviest load, is interpreted as being supplied by the two most common areas found within the electrical grid, which are residential/commercial loads and industrial loads. Part of the load is considered to be residential, but the majority is considered to be an industrial load. The industrial load is modeled as being two different load profiles, first a small static load which is similar to that of the residential and commercial loads, and then a dynamic load. In total, the dynamic load represents roughly one-third of the load at Bus 180. This leads to the total harmonic machine load of one-fifth of the total load within the island, or roughly 1.2 MW of dynamic load within the island.

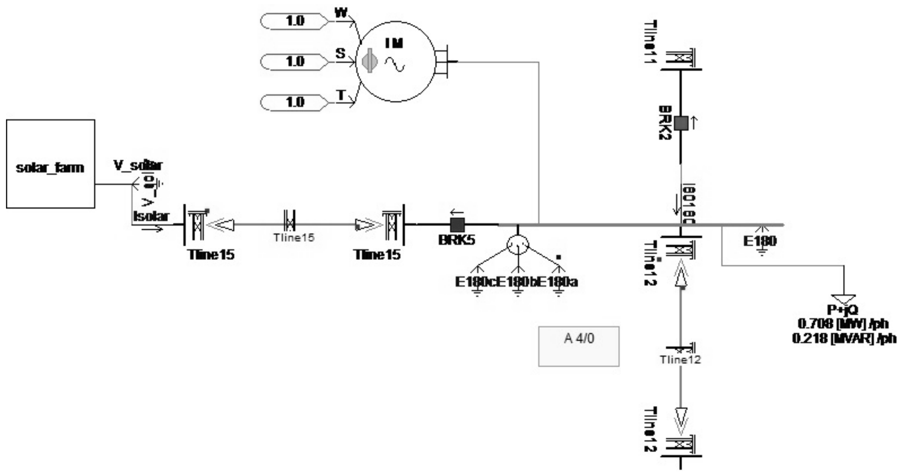

Figure 3.6: Machine Load Within the Island

After conducting several simulations utilizing the harmonic parameters, a definite pattern concerning the harmonics was seen, namely that very few harmonics were generated. This can be attributed to several reasons within the simulation, the first being the relatively small size of the solar generation relative to the other sources of generation. With a nameplate ratio of 10:1 between the wind and solar generation, even if 10% of the solar generation was harmonically distorted, this only translates to 1% of the overall power generation becoming distorted. Additionally, the solar generation also contains a simple low-pass filter as part of its design, effectively eliminating higher-frequency harmonics from being passed on to the rest of the system. The final limiting factor is the stability of the backup generation, which helps to keep the machine loads from injecting many harmonics back into the grid. Therefore it was decided that for the purposes of harmonic study, a different model with significantly more solar generation along with a controlled source of harmonic injection would be more suited to a complete study of its own.

Although harmonics are a real possibility with distributed generation that contains electronic control, there are several measures that can mitigate their effects. These include using a low-pass filter with the solar generation and making sure that the solar generation does not become a dominant factor in the generation portfolio. In this way, the non-ideal loading can be appropriately handled and will not be worsened through the inclusion of electronically-controlled renewable generation.

3.5 Summary and Differences of Load Profile

Long-term changes within the load by season, situational deviations within the system, and non-static variations such as harmonic loads that can affect other areas that have not been typically analyzed in past studies. However, as half of the generation-demand equation, changes in load can have significant impacts in the value of renewable resources. The solutions to these different areas of needed change are the creation of a dynamic load profile, an imbalance in the loading at each bus in the model of the distribution system, and the creation of a harmonic load in conjunction with the solar generation. For dynamic loading, the profile of the load over the seasons was modeled to coincide with the wind and solar resources. This was done by creating a theoretical day for each season, which provides a profile to compare the generation of the renewable resources. To create a realistic scenario of loading conditions in a distribution system, imbalance was introduced into the system with the loads at the various buses altered to be disproportionate among the three phases; additionally, a harmonic study was created to investigate the impact of non-linear loads on the system.

CHAPTER FOUR

TRANSIENT ANALYSIS USING PSCAD SIMULATIONS

4.1 Overview of PSCAD Model and Introduction to Simulations

To properly understand the effects of introducing distributed renewable generation into a distribution system, a suitable transient time-frame simulation is needed for the system. One program that is capable of carrying out this type of simulation is PSCAD, which allows for a wide variety of electrical power systems to be modeled and simulated for both transient and steady-state time frames. All that was required was to properly tailor the system for being run in the PSCAD environment. The first area that had to be detailed was the construction of the model in PSCAD from the extant model of the distribution system, with modifications for the renewable resources. To better understand the specifics of the renewable resources utilized within the research, the models used for these resources will be detailed as well. The next step was to adapt the scenarios created for the study to be specifically modeled for the simulation environment. Finally, the results for the different scenarios and simulations are presented to create a picture of the expected operational transients of the system.

4.2 Islanding System with Wind and Solar Generation

Because this analysis relies heavily upon the effects introduced by the addition of the wind turbine and solar panels, it is important to study these elements more closely. Specifically, some of the parameters that were implemented specifically for the DFIG and the solar panels will be detailed, and also how these models were made to work together to provide a healthy environment for the islanding simulations.

The models of these technologies attempt to mimic the controls and the parameters that renewable technology uses, from maximum power point tracking for the solar panels to the mechanical parameters of the wind turbine used for the wind farm. For the solar panels used for this research, the system controls and behavior worked quite well, and required no modification insofar as control was concerned. The only substantive change that had to be made of the system, which consists of two solar arrays in parallel, each with their own set of inverters (as seen in Figure 4.1) was to increase the output of the panels to fit the theoretical parameters. This was accomplished by increasing the number of cells in parallel for each solar module to 8, and the number of modules in parallel for an array to 20. By increasing this parameter, only the current was increased for the system to gain greater power, which allowed for the same voltage parameters to be utilized both for the inverters and transformers.

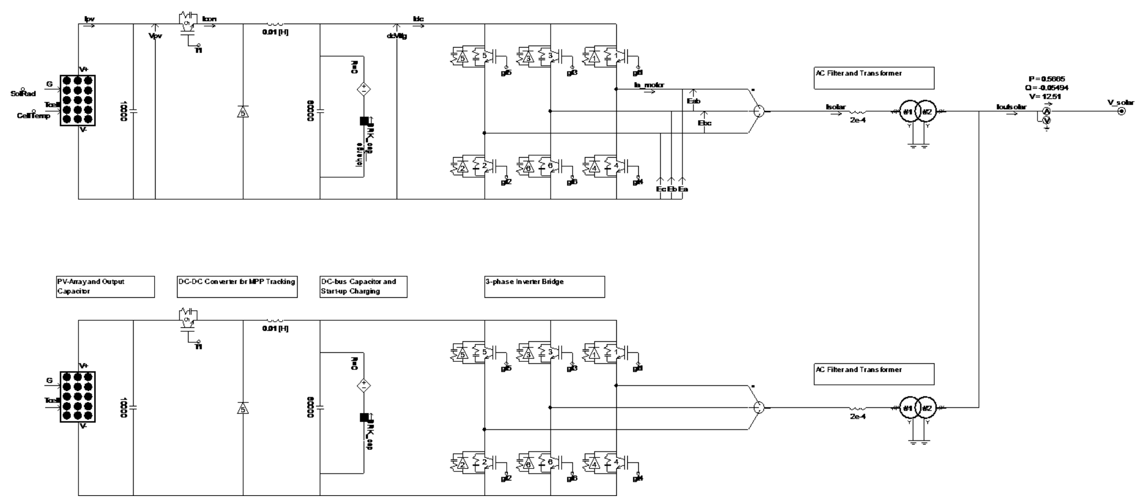

Figure 4.1: Solar Farm as Modeled in PSCAD

While the solar farm was relatively simple to implement in this study, several changes were necessary to the DFIG model utilized by PSCAD to make it suitable for the system parameters. This was due to the fact that the wind generation model was slightly more complex than the solar model in its controls and parameters. The first item that had to be changed was a modification of the transformer ratios to accommodate the voltage levels of the distribution system. Next, the size of the generator was increased by changing the MVA rating of the DFIG to what was required for the simulation. In the case of moderate wind, this was a level of 4 MVA, and for full wind power this was modified to 8 MVA. A final parameter change that was required for the smooth operation of the system was a modification of the reference torque for the turbine, which by default has a shift down after 8 seconds, which was implemented by the developers to display the dynamic reaction of the controls. For the sake of this research, however, that caused an unnecessary shift in the output power, and was therefore modified to keep the reference torque constant.

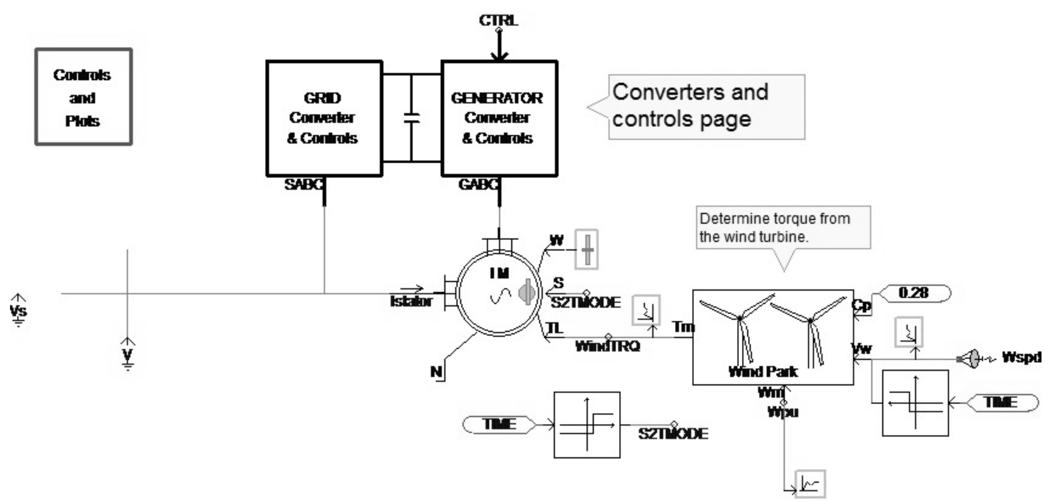

Figure 4.2: Overview of Wind Farm Model

After these models were understood and implemented, the parameters for the operation of these elements in concert were set to properly coordinate with the switching and backup generation.

- Switching operations were set for at least 4 seconds after initialization to let starting transients diminish.
- The backup generation power limit was intentionally capped at a level close to its expected output, to prevent the simulation from allowing it to produce more than needed and displace renewable generation.
- The wind turbine's input torque was modified after 8 seconds to keep a constant profile throughout the simulation.
- As the solar and wind resources were not considered "dispatchable" they were not switched in and out of the system.

With the proper solar and wind models, needed adaptations for the DFIG turbine, and coordination of the renewable elements with the island and backup generation, the simulation can provide a much more accurate picture of the expected effects. The models, having been designed by the development team, proved to be accurate and useful to the research, having parameters which were easily modified for specific scenarios. With properly defined operations to coordinate the backup and renewable generation, the system was ready to be assigned specific scenarios for simulation to reflect the theoretical models.

4.3 Adaptation of Scenarios to PSCAD Environment

As the scenarios developed for the probability and overall analysis are quite broad in their scope, they must be adapted for the PSCAD simulations, to represent as generally as possible the different scenarios of the probability analysis.

- As the probability analysis is a continuum with few fixed cut-off points, several concrete scenarios must be constructed within the simulation environment.
- Typical switch times needed to be selected for the cases to provide a standard by which to compare the different results.
- Load levels had to remain constant inside the PSCAD environment, although they were dynamic within the probability analysis.
- The concept of fault or disturbance switching was an element that entirely consisted of the effects produced on a transient level, and is therefore unique to the simulation environment.

First, the different scenarios which should be simulated for were determined for their ability to represent the overall picture of the probability analysis. With the parameters for levels of solar and wind generation fixed as discussed previously, this then began to lay a framework for the potential scenarios that would be simulated. The basic breakdown was to have simulations for just solar power or wind power, then a combination of the two. The combination of the two then could also be a choice between a moderate amount of wind, and a full wind generation scenario. These scenarios were modified as detailed in previous chapters to reflect disturbances such as faults, and additionally scenarios of connecting the island back into the grid. These fixed-level scenarios then could provide the information for the scenarios previously outlined in the theoretical parameters.

As there are two major cases for which simulations were carried out, which were the balanced load case and the unbalanced load case, there were specific distinctions between the two cases. The unbalanced load case was critical, as all realistic distribution systems have some level of unbalance within the system. For the simulation environment, the difference in the base case and unbalanced case reflected the rotation of a diminished power phase throughout the system, to reflect the splitting of the load to maintain a degree of balance from the perspective of the substation transformer. From the perspective of the renewable generation, however, this left a larger unbalance in the island, which was reflected in the simulation results as larger transient currents in response to system disturbances, as well as longer periods for the system to restore to a normal state. The specific load levels for the load unbalance were kept the same as previously calculated in the theoretical development. Additionally, several cases for solar power were examined, such single-phase solar power in representation of a subdivision which used solar panel power support, which further contributed to the unbalance of the system. In keeping with the previous rotational methodology, this generation was placed on the most heavily loaded phase from the island's viewpoint, so the unbalance in the form of solar generation actually served to mitigate the unbalance of the island as a whole.

There were also a small number of esoteric cases created for study, which included the previously mentioned harmonic study and one-phase solar, and a case that included a simulated battery with the solar farm. For most of these cases, the effects created by the variants were quite small, so they only merited a minor investigation. For the harmonic study the implementation of controls and filters within the solar farm minimized the harmonics to only a trace amount. For the battery study, a model of a battery utilized previously was added to the system in the solar farm [27], but its inclusion created no difference in transient effects, and only served to slightly modify the output of the solar farm down while charging, and up while discharging. The most interesting case was that of single-phase solar, which was beneficial in helping to balance the generation and load of the island, but could also produce greater unbalance in the transients during a switching operation. However, as this was still limited by the small size of the solar panels' power output, its impact was minimal.

These different scenario cases then are able to reflect the differences in the potential ways that the system could be implemented between the actual world and simulated environment.

Table 4.1: Scenarios for Simulation

Scenario #	Balanced/Unbalanced	Wind Generation	Solar Generation	Special note
1	Balanced	Yes	No	
2	Balanced	No	Yes	
3	Balanced	Yes	Yes	Mid and Full Wind
4	Balanced	Yes	No	Fault
5	Balanced	No	Yes	Fault
6	Balanced	Yes	Yes	Fault
8	Unbalanced	Yes	No	
9	Unbalanced	No	Yes	
10	Unbalanced	Yes	Yes	Mid and Full Wind
11	Unbalanced	Yes	No	Fault
12	Unbalanced	No	Yes	Fault
13	Unbalanced	Yes	Yes	Fault

4.4 Results

The results produced from such a broad course of study are difficult to encapsulate fully, but there are several key results for each scenario that must be presented.

First, some of the most interesting and pertinent results for each scenario are presented to give an understanding of the operation of the system under different operating scenarios. First is the observation of the base case with intentional islanding how smoothly the system transitions from one state to another. The only noticed effect is a slight rise in the voltage profile, which for a system with voltage regulation would not present much of an issue.

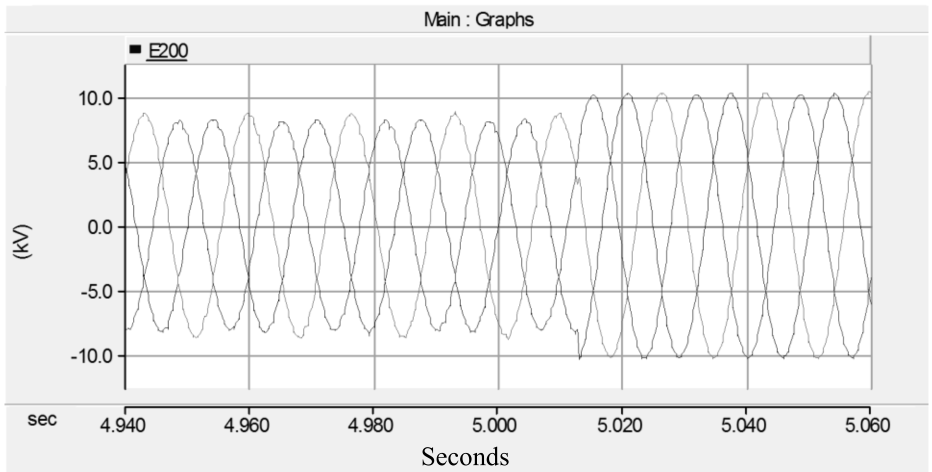

Figure 4.3: Voltage Rise After Islanding

In the unintentional islanding scenario, one of the interesting effects that can be noticed is the island feeder current during and after a fault event, which displays irregularity as the power generation of the renewable resources are drawn into the fault. Instead of increasing as expected, the loss of reactive power support actually causes current from the renewables to slightly diminish before islanding where a small spike in current in noticeable as a transient effect.

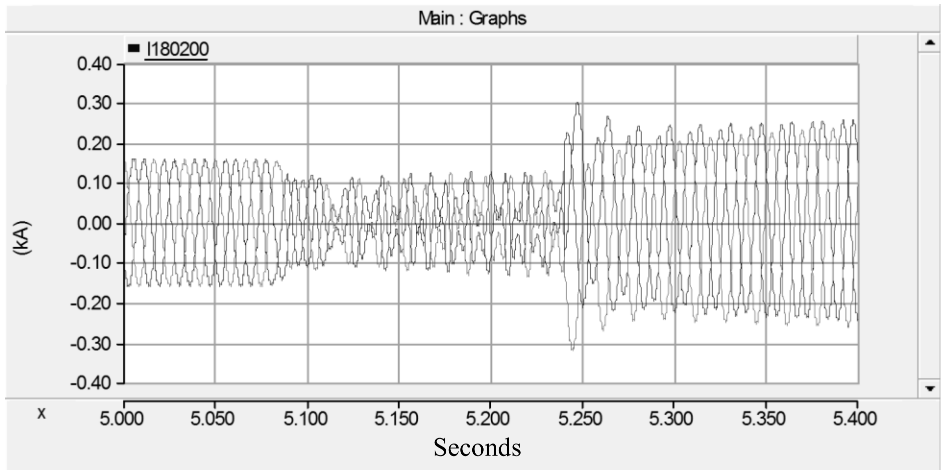

Figure 4.4: Island Feeder Current during Fault and Islanding

For the reconnection scenario, one of the more interesting effects is to note how the generation itself can be affected by the change in system topology. The solar generation during reconnection may experience a period of unbalance in its generation, seen in the following capture. Often, these changes in the solar output are driven by the reaction to the changes in the wind generation, but for this scenario the effect is a direct result of the solar controls adapting to the reconnection of the island to the main system.

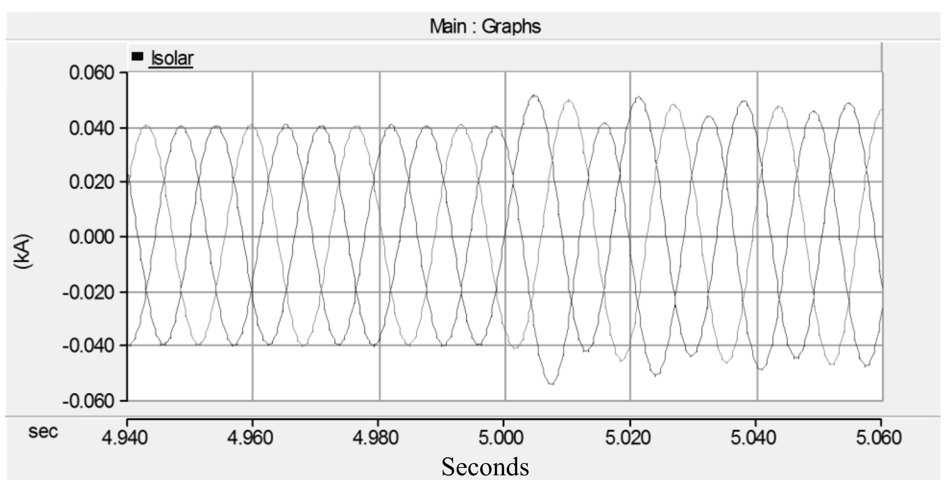

Figure 4.5: Solar Generation Current during Reconnection

One of the most interesting scenarios is that of the single-phase solar generation, which was implemented to help mitigate the effects of unbalance within the system. However, because of the different possible levels of solar generation, a significant amount of unbalance may remain in the system. This is evidenced by the following figure, where the feeder current between the buses in the system is distorted due to the generation of current on only one phase. While this is not a problem for system health, this could prove to be problematic for protection schemes that use differential relays to protect the system.

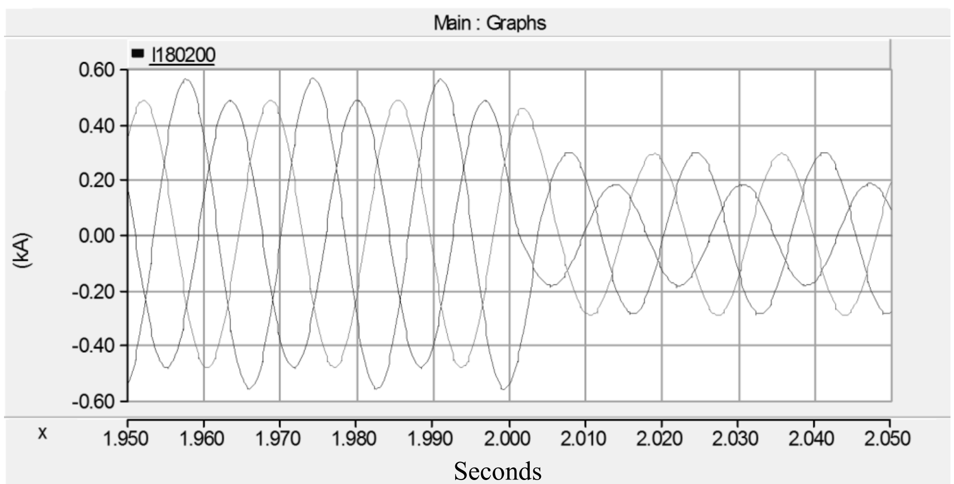

Figure 4.6: Feeder Current Imbalance with Single-Phase Solar

Additionally, the differences between the balanced and unbalanced cases must be noted, as this is one of the primary differences between this study and previous studies. Some of the important contrasts found between the study of the base case and of the unbalanced case are as follows:

- In the unbalanced case, transients become exaggerated as one phase typically draws greater currents.

- Base case fault clearings return to a normal state more quickly than the unbalanced case.
- Although the current profiles and sometimes even the voltage profiles may change for the unbalanced scenarios, overall the generation output is not noticeably affected.
- A more noticeable effect of the unbalance is the creation of divergence within the phases during a switching operation, as each phase reacts more independently than what appears in the base case.

One of the most meaningful results that can be gleaned from the simulations for the different scenarios are the different power output profiles from the system. This provides an insight into the interplay of the renewable generation, which is dominated by the wind generation. This is most clearly evidenced when the wind generation provides the greatest part of the generation, as seen in the following figure. This provides a glimpse of how the wind generation, even with a steady reference torque and wind speed, may not quickly converge to a steady output.

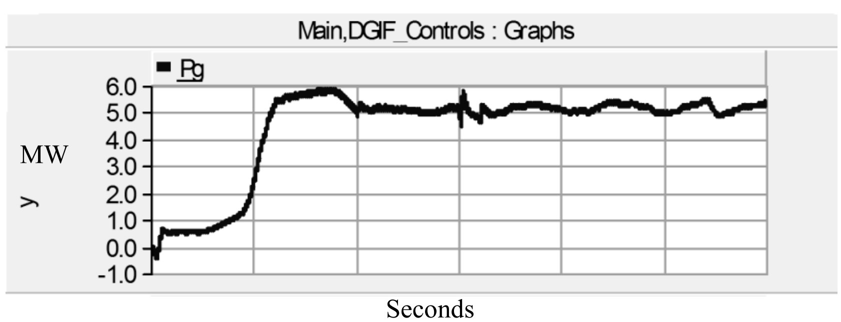

Figure 4.7: Movement in Wind Generation

In response to these movements in the wind generation, the backup generation must then also move in order to match load and generation, resulting in the very dynamic output profile seen in the next figure. Notice how the changes in the conventional backup closely follow supporting the wind generation, especially after the initial 3 second transients die away.

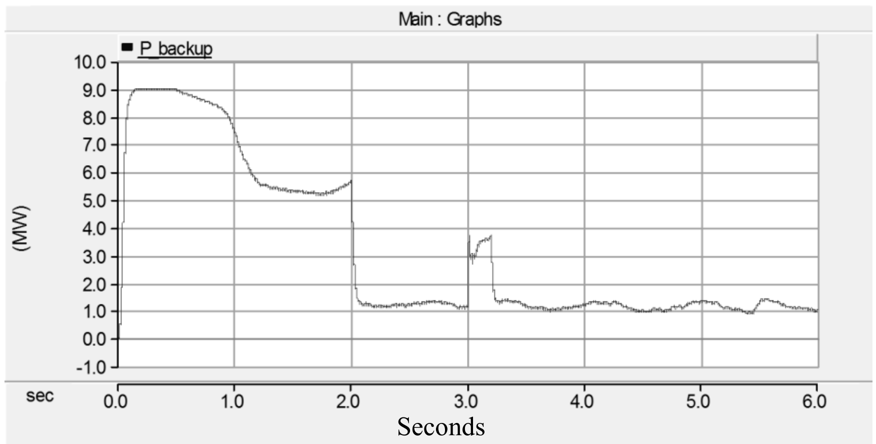

Figure 4.8: Changes in Conventional Backup Generation

In contrast to the wandering generation profile of the wind resource, the solar resource provides a very steady and constant output profile, after two initial control transients are allowed to die away.

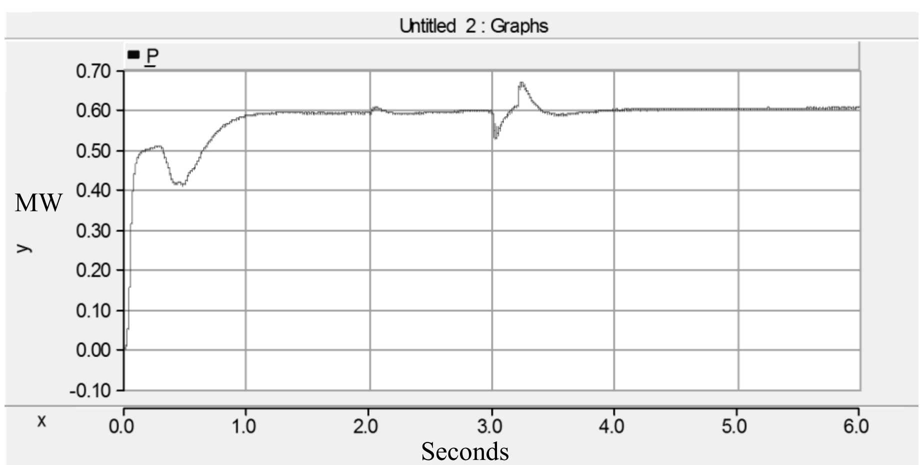

Figure 4.9: Solar Generation Output Profile

The best combination appears to be to have a healthy amount of solar generation, a moderate amount of wind generation, and allow the rest to be contributed by the backup generation. This allows for a much smoother and more easily controlled output profile, as evidenced by the final figure showing moderate wind contribution. Besides the dip to allow for backup generation to come online, it converges to a steady state much more quickly than the fully powered wind generation scenario.

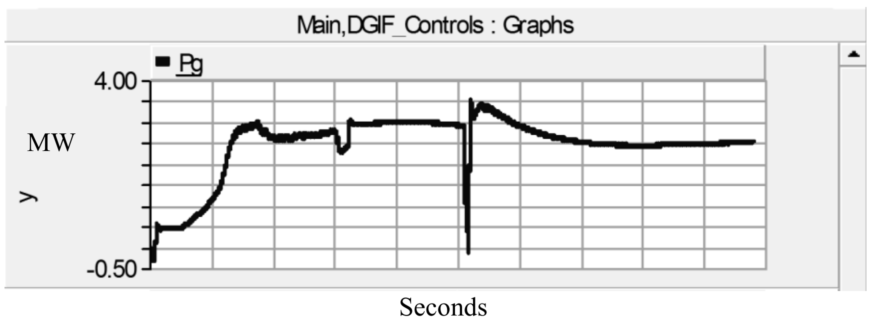

Figure 4.10: Steadier Moderate Wind Generation

Although only a sampling of the different results are generated from the different simulations, the overall operations of the system can be understood from these different results. The voltage and current profiles provide a good idea of the continuous health of the system and the type of controls and protection needed. In addition to this, the generation profiles give insight into the interoperation of the renewable resources, and allow for different sources of power generation.

4.5 Summary of PSCAD System and Parameters

From each of the different steps to complete these simulations, something important can be learned regarding the incorporation of renewable resources into the distribution system. By constructing the base model, it can be seen how the location of the energy sources can have an impact on the unbalanced system's operations. Also, specific modeling for the generation of the renewables is critical, as control systems are quite diverse and it may change greatly from the DFIG used here, and other types of wind generation such as a singly-fed induction generator (SFIG). After the scenarios of the probability analysis were adapted for the simulation environment, the results could be gathered, which were very informative as to how the system might behave. It reinforces the ideas that large amounts of wind penetration in generation must be used with caution, as this can affect the ability of the system to quickly come to a steady-state situation, and with changing wind speeds it is possible that full convergence could not be maintained.

CHAPTER FIVE

PROBABILITY ANALYSIS OF RENEWABLE RESOURCES FOR ISLANDED SYSTEM

5.1 Introduction to Probability Analysis for Renewable Resources

The field of probability analysis is broad and touches virtually every engineering field. For utilities, deterministic methods and control techniques are used to create a stable grid that is both reliable and secure, and probability analyses are often unnecessary. However, the modern developing grid will be introducing non-deterministic elements such as renewable resources, which have stochastic (essentially random) characteristics. Therefore, accurate non-deterministic methods must be introduced to the industry to maintain the standards of reliable and secure operation that have been achieved.

Probability analysis has broad applications, but its usefulness to the electrical grid has only been recently explored due to the fact that the operations of the grid are deterministic in nature, as the unknown variable in the generation-transmission-consumption situation has always been the load. However, the introduction of renewable resources places uncertainty in the generation as well. If a method can be utilized to eliminate as much of this uncertainty as possible, that will aid in their incorporation into the grid because of increased economy and confidence. For the solar resource, this is a function of time and cloud cover, and therefore is quite straightforward to estimate in comparison to the wind resource, which can be highly variable. The wind also receives added focus as it is expected to contribute much more overall power to the global generation in the future than photovoltaic resources.

Therefore, in this chapter the mathematical parameters describing the solar and wind resources for probability analysis will be detailed, along with how this translates into practical power output and application. The specific parameters for the probability analysis will also be given, in addition to several proposed modifications for alternately investigating solar probability. Finally, the results of the probability study will be introduced and detailed for the coastal region under study, which can provide a glimpse of the usefulness of such a study.

5.2 Solar Probability Analysis and Modifications

The easier of the two renewable resources to characterize using probability analysis is solar power, as it is determined by a steady driver in the sun, and is modified from this by atmospheric conditions. To fully understand the probability analysis of this resource, first the generation of the power from the photovoltaics is discussed, and how this has been classically calculated using statistical means. Next, alternatives to this method will be presented to achieve greater clarity and ease of use in the calculation.

The output from solar panels is largely based on the amount of solar irradiance which the panels receive. It will be determined by the atmospheric conditions (cloud cover), time of day, and season. A basic solar panel operates much as a variable resistor with the basic parameters of open circuit voltage and short circuit currents, which provide the maximums of the panel [9]. As the voltage decreases, the current increases until it reaches the short circuit value and stays essentially the same as the voltage approaches zero. Likewise, as the voltage increases, the current begins to exponentially decline until it reaches zero at the open circuit voltage [9]. The point at which the maximum power is able to be extracted from the panel is at the knee point of this curve characteristic, and often they are operated with slightly lower voltage than this in order to prevent a drastic loss of current in case the voltage rises [9]. The figure below demonstrates this point of operation, with data parameters taken from [9].

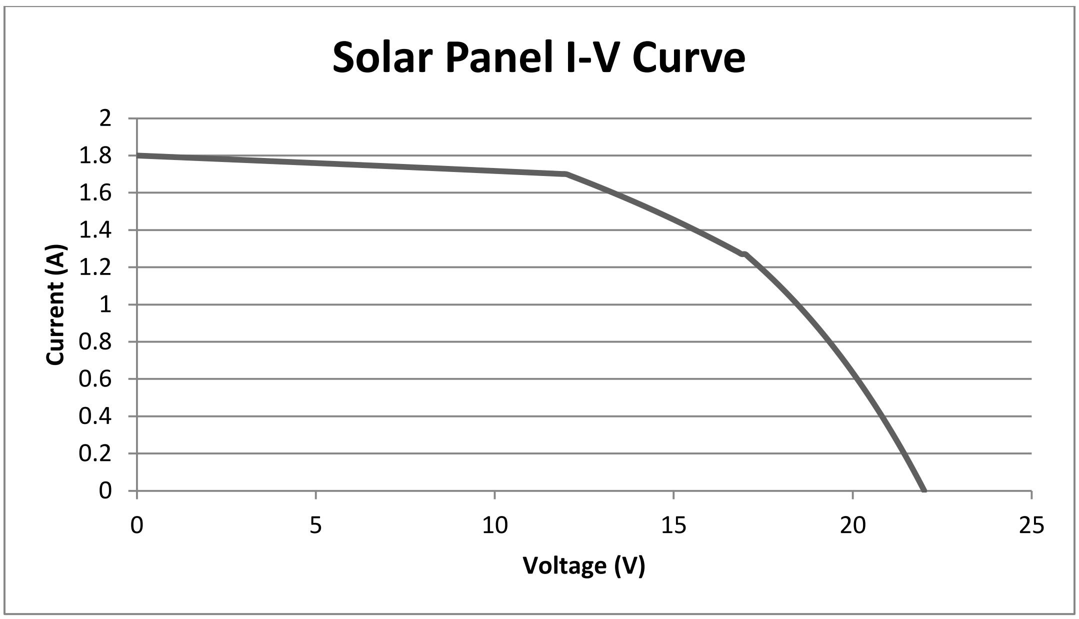

Figure 5.1: I-V Characteristic of Solar Panel

There are three primary factors which affect the power output of a given solar panel, and these are the amount of radiation received by the panel, the temperature of the panel, and the ability to maintain the correct current and voltage to maintain maximum power output. For the first consideration, differences in solar radiation cause small differences in the voltage of the solar cell as well as the current, and thus the entire power curve is shifted with the amount of radiation received. Essentially, the less light received, the lower the efficiency of the cells to produce maximum output, which is demonstrated in the following figure [9].

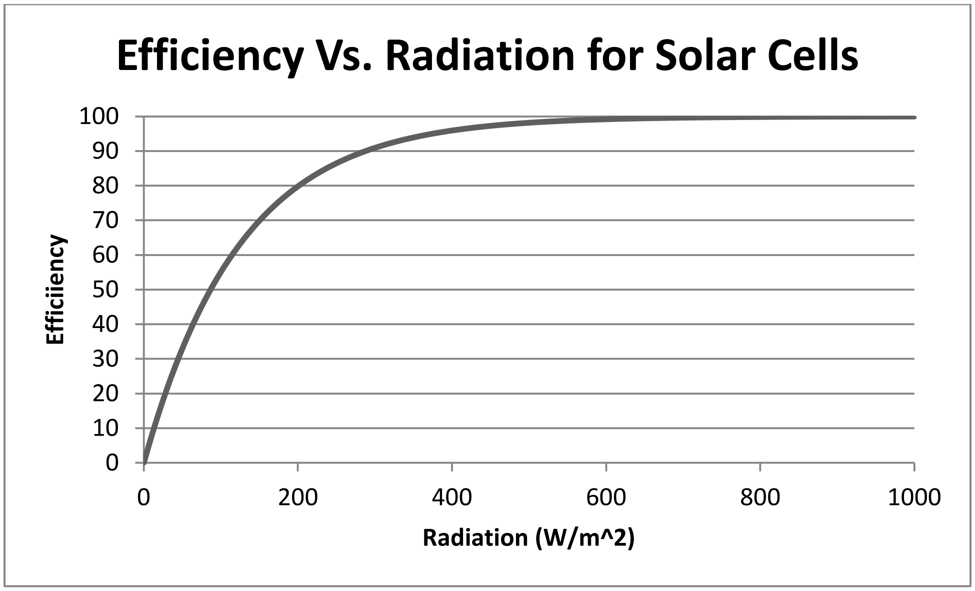

Figure 5.2: Example of Solar Cell Efficiency

The next consideration for solar cell efficiency is that of the ambient temperature of the cells. In higher temperatures, the cell loses efficiency, and is one of the reasons that solar cells are known to perform better with cooler temperatures and good amounts of sunlight. This leads to a small paradox within solar arrays, in that during the summertime when solar irradiance is greatest, the efficiency of the cells is decreased. However, manufacturers and utilities often do not model the changes in the panels due to temperature, even though it can cause a very real change in the power output [9]. According to literature, the typical solar panel loses about 0.45% power output efficiency for every degree Celsius the temperature is raised [9]. For the temperature range of the region in which the current system is being considered, this gives a practical working range of roughly 35 degrees Celsius. This is the assumption that under optimal solar irradiance conditions, the temperature range would vary from 40 degrees Fahrenheit to 100 degrees Fahrenheit, which is a slightly larger range than needed to characterize the midday temperatures associated with spring and summer. This then gives an efficiency drop of 15.75% which in terms of the power output for the solar cell is not a negligible amount. However, for the current functions being investigated, it is not necessary to include it in the probability density function. With the preceding consideration of increased efficiency with increasing solar irradiance, and the fact that there is more solar irradiance in warmer months, this is mitigation enough to not include the temperature in the model as currently constructed. Therefore, the basic formula for determining the output of the solar panels is estimated by the following equation:

$$P(solar) = \frac{Radiation\ received}{Maximum\ radiation} * P_r \quad (5.1)$$

However, for a more detailed study, a formula to start with rectifying this discrepancy can be calculated as:

$$P(solar) = \left(1 - \left(\frac{40-C}{40}\right) * .0045\right) * \frac{Radiation\ received}{Maximum\ radiation} * P_r \quad (5.2)$$

Another consideration for the efficiency of the solar cells is that of maximum power point tracking, which is necessary in order to maintain the peak output of the cell at all times. As shown above, the efficiency of the solar cell increases with decreased temperatures, but this efficiency can be missed if the cells are not operated properly. This is because the decreased temperatures also shift the knee point at which the maximum power output of the cells are reached, meaning to extract maximum power the voltage of the cells must be lowered [9]. This is achieved through technology known as maximum power point trackers, which allow the cells to be adaptively run at the voltage level where the maximum power output is achieved.

The area of probability analysis for solar generation in previous studies is more complicated than that of wind generation, and has been traditionally dependent on a number of factors that are difficult to obtain and parameterize. The prevailing form of probability density function that has been utilized for the field of solar analysis takes the form of the pdf for the clearness index, which is a measure of the atmospheric conditions that allow solar radiation through to the earth's surface, essentially cloud cover [28]. This is obtained by utilizing the pdf as:

$$P(k_t) = C * \frac{(k_{tu} - k_t)}{k_t} * exp(\lambda * k_t) \tag{5.3}$$

where the parameter k_t represents the hourly clearness index. C and λ are found by using the maximum and mean of the clearness index, which are k_{tu} and k_{tm}, respectively [28]. The following formula is to obtaining the factor C as:

$$C = \frac{\lambda^2 * k_{tu}}{[exp(\lambda * k_{tu}) - 1 - \lambda * k_{tu}]} \tag{5.4}$$

To obtain the C factor, the λ factor must then already be known, and it is calculated using the formula:

$$\lambda = \frac{2\gamma - 17.159 exp(-1.3118\gamma) - 1062 \exp(-5.0426\gamma)}{k_{tu}} \tag{5.5}$$

Again, this introduces a new variable, γ, which is also derived using parameters from the clearness index. The parameter γ is derived by the following equation;

$$\gamma = \frac{k_{tu}}{k_{tu} - k_{tm}} \tag{5.6}$$

which is the final parameter necessary to categorize the pdf.

This can be used to construct a formula that is capable of calculating the solar irradiance on any tilted surface as:

$$I_{\beta} = \left[R_b + \left(\frac{1+cos\beta}{2} - R_b\right) * k + \rho * \frac{1-cos\beta}{2}\right] * I_t \qquad (5.7)$$

Which then introduces several new variables, namely R_b, β, k, ρ, and I_t. The variable R_b is the ratio of a beam of radiation on a tilted surface to that on a horizontal surface. The variable k is the fraction of the radiation that is diffused on the horizontal plane, ρ is the reflectance of the ground, and β is the inclination of the surface to the ground. The variable I_t is calculated by using the following equation:

$$I_t = I_o * k_t \qquad (5.8)$$

The next step is to construct the cdf of the probability density function, which in this case is necessary to use integration by parts. The resulting cdf is:

$$cdf(k_t) = \frac{C}{\lambda} * \left[\left(\frac{\lambda * k_{tu} + 1 - \lambda * k_t}{\lambda * k_{tu}}\right) * exp(\lambda * k_t)\right] + c \qquad (5.9)$$

where c is the constant of integration. Because the area of a pdf is always equal to one, this constant can be solved for by setting the cdf equal to one and solving for c. Doing this yields the value of

$$c = -\frac{C}{\lambda}\left(1 + \frac{1}{\lambda * k_{tu}}\right) \qquad (5.10)$$

which is the constant of integration for the cdf.

However, this approach to reconstructing the probability for the solar irradiance has several issues that would make it unattractive to implementation to utilities or power cooperatives that may be looking to integrate solar generation into their system. First of all, the complexity of the equations, along with the multiple assumptions that the equations require, create complexity that might hinder implementation. Additionally, the equations rely on several variables that are both specific to each situation of installation and difficult to obtain in any quantity and consistency to create a meaningful study. Additionally, the clearness index has one aspect that would seem to make it an undesirable means of measuring the solar irradiance: it simply depends on atmospheric conditions, and ignores the primary driver of solar irradiance, which is the relative position (angle) of the sun to the earth.

It would seem that a more practical way of deriving the solar probability is to use a more direct measure of the solar irradiance within the context of a straightforward function that can be easily adapted to different situations. This has been done before in other studies, where the solar irradiance was characterized by a few simple parameters that allowed for a flexible analysis to be carried out [29]. One way to begin accomplishing this is by using the measure of solar irradiance that has been developed known as METSTAT, which is a solar radiation model that was developed for the National Solar Radiation Database that uses a vast array of information and parameters to construct the amount of solar irradiance accurately, even when there are gaps within the measured irradiance. Typical parameters that are used within this study include the cloud cover as associated with the clearness index, along with different measures such as atmospheric pressure and aerosol depth. With a measure such as this in place, a simpler probability density function can be created. With this new data, a simple normal distribution model appeared to be a good place from which to begin, as the sun should provide a fairly consistent output which is then affected by randomized events such as cloud cover. This then yields the simple formula as:

$$f(solar) = \frac{1}{\sigma * \sqrt{2\pi}} * exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \quad (5.11)$$

where μ is the mean of the METSTAT measure, and σ is the standard deviation. An interesting aspect of the Gaussian (or normal) distribution is that it cannot be integrated in a deterministic manner, meaning that results for the integration of the evaluation of the pdf must be numerically integrated [30]. However, this is not a problem for modern software tools such as Matlab, meaning the integral of the normal distribution can be evaluated as easily as any other type of function.

Even though the normal distribution is a well-used standard with which to characterize much natural phenomena, it is almost certain that an even better means of characterization for solar irradiance can be found. One of the mains flaws of the normal distribution for analyzing the solar output can be found in the fact that in the normal model proposed, the sun's relative position sets the point from which the cloud cover and other variables create deviation. However, under logical analysis, this leads to an inaccuracy, for if the sun's position determines essentially the mean, the rest of the variables from the normal distribution must then be able to produce an increase in the solar irradiance as well as a decrease, in order to produce the perfectly symmetrical bell curve of the normal distribution. Logically, the position of the sun in the sky should actually produce a maximum, from which the cloud cover and other factors can then produce a negative deviation. One function that is capable of producing such a distribution function is the Rayleigh function, which has the following formula:

$$f(x) = \frac{x}{b} * exp\left(\frac{-(x^2)}{2b}\right) \tag{5.12}$$

for its probability density function, and likewise

$$F_X(x) = 1 - exp\left(\frac{-(x^2)}{2b}\right) \tag{5.13}$$

for its cumulative distribution function. Below is an example of a typical Rayleigh function.

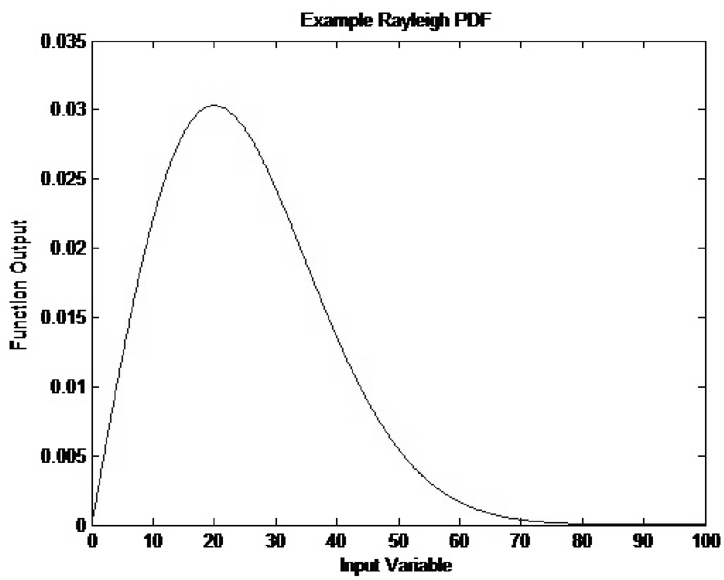

Figure 5.3: Example Rayleigh PDF

Much as the comparative study of the wind speeds, the pdfs of the solar output can be compared to the recorded data of the solar irradiance and analyzed to find which function most closely approximates reality.

By using these different techniques, the solar probability can be obtained with a great degree of confidence. By knowing the factors within the panels that affect their performance, effective power production models can be made for the solar resource. Additionally, even though the traditionally used means of analyzing the solar resource are extremely complex, more straightforward methods have the potential to make this more practical for broader investigation.

5.3 Wind Probability Analysis and Parameters

Wind possesses unique qualities that make it suitable for probability analysis, but not in one of the more common probability density function families. Typical probability density function families include normal (Gaussian) distribution, uniform distribution, Poisson distribution, and so on. However, these types of distribution are often symmetrical in some way around a specific point probability. Wind has the unique quality in that it can be sustained, and thus roughly center around a given wind speed, but it can also be intermittent, in which case it then becomes a function that returns to zero. The function that to date has been able to characterize this type of behavior most accurately and flexibly is the Weibull function [31].

The Weibull function has the ability to be quite nearly normal in distribution, centering around a specific point, and also skewed towards zero based on the input of very simple parameters.

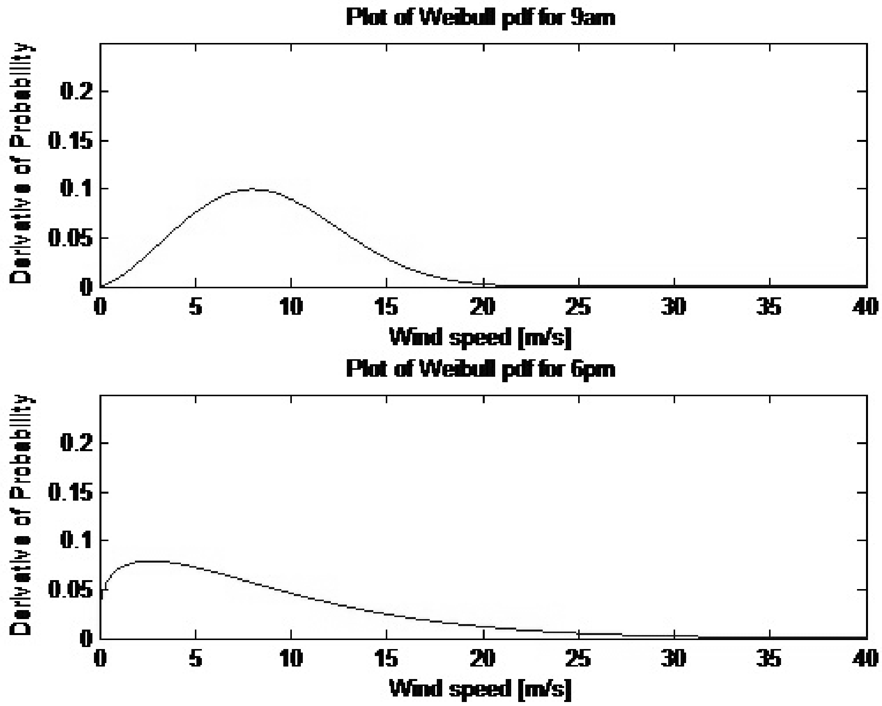

Figure 5.4: Variants in Weibull Function Profiles

With the Weibull function developed for the wind speed, the accuracy of these data can be analyzed in light of the available data. Concisely, since there are a large number of data points of the wind speed, the probability can be tested with regards to the actual results. The accuracy of the probability density function can be evaluated by using a statistical tool known as correlation, which is a measure of statistical dependence. Statistical dependence is the relationship between two different functions, whether or not the output of the one corresponds with the output of the other. The normalized value of this correlation is known as the correlation coefficient, and is determined by:

$$\rho_{xy} = \frac{Cov(X,Y)}{\sqrt{Var(X)*Var(Y)}} \tag{5.14}$$

where Cov(X,Y) is the covariance between the two functions, and Var(X) is the variance of the function [30]. By using this correlation coefficient, the efficacy of the Weibull function can be evaluated with regard to the actual data, and can be viewed in light of other functions, much in the same way that the adequacy of the alternative methods for investigating solar probability are evaluated.

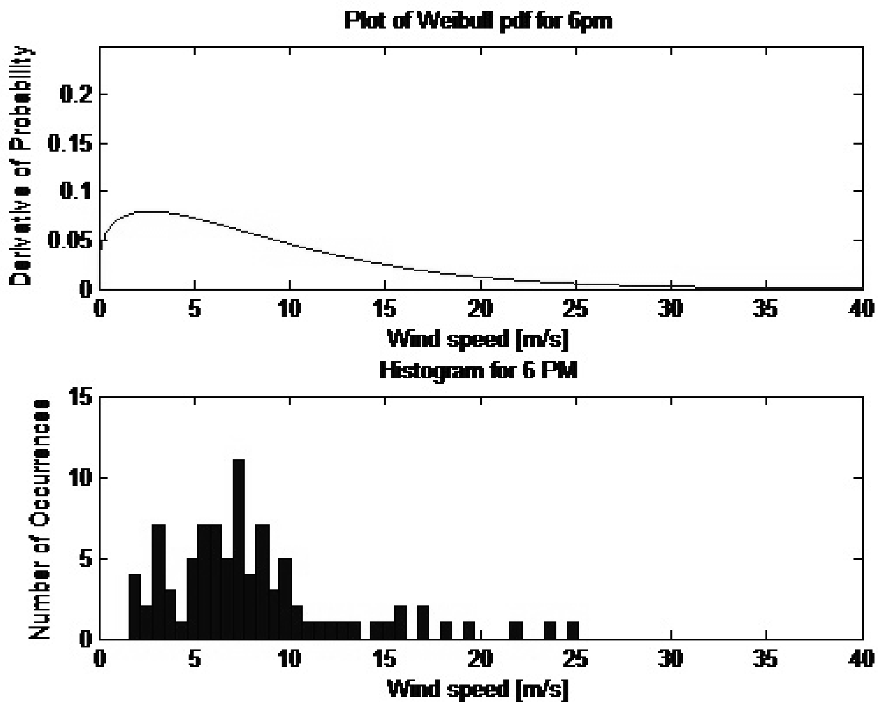

Figure 5.5: Example of Histogram vs. PDF

The additional functions that this can be compared to are those of the Gaussian distribution and the uniform distribution, which are both simple functions used to determine many natural phenomena.

To construct a Weibull function for wind speed, all that is needed are the current wind speed, the mean wind speed, and the standard deviation of the wind speed. Mathematically, the Weibull function is modeled as follows:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} * \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{5.15}$$

In this function, the parameters that set up the pdf are the *k* and *c* parameters, and the variable in the equation is *v*, which is the wind velocity. The *k* parameter, which is known as the shape factor, is found by the following formula:

$$k = \left(\frac{\sigma}{\mu}\right)^{-1.086} \tag{5.16}$$

where σ is the standard deviation of the wind speed over the recorded wind values, and μ is the mean value of the recorded wind speed [32]. This differs from the way in which the shape factor is typically determined, which is often arbitrarily selected beforehand [9]. However, this method of determining the shape factor from the wind data itself is more likely to produce accurate results, as wind profiles not only change drastically from one region to another, but also from one part of the day to another. The shape factor ultimately sets what the pdf will look like, whether it will mimic a normal distribution, or more of an exponential decreasing from the origin. The most common form which the Weibull function takes is that of a normal distribution that appears to have been shifted non-uniformly to the origin, which mimics the Rayleigh function [9]. Additionally, *c*, which is the scale parameter, is determined by the following equation:

$$c = \frac{\mu}{\Gamma(1+{}^{1}/_{k})} \tag{5.17}$$

where the gamma function, Γ, is used in conjunction with the shape parameter and mean to determine the scale of the pdf. This scale factor determines the concentration of the pdf, and helps to characterize wheter the wind is gusty and has a large range, or rather consistent with a narrower range. This pdf function helps to graphically visualize the behavior of the wind. For actual calculation purposes it is much easier to work with the cumulative distribution function, or cdf, which is the integral of the pdf. In this case, the cdf of the Weibull function is as follows:

$$F(v) = 1 - exp\left[-\left(\frac{v}{c}\right)^k\right] \tag{5.18}$$

This form of the function lends itself more easily to the processing of numbers to obtain the probabilities of certain ranges, and therefore is of value in the analysis.

Although the probability calculations can provide an analysis of the availability of the resources themselves, it takes additional mathematical steps to translate this into a power output that can be utilized for simulations. By doing so, the condition of a system can be determined simply by finding the conditions that characterize the renewable resources [33]. If the total energy output by the renewable resources is desired, the probability density functions of the power output can be convolved and integrated into a total energy output for the resources [34]. The output of power generated by wind is specific to each particular type of turbine, but each turbine can be characterized by a generic output profile that is broken into several different stages [35]. This output can be described by the following piecewise function:

$$P_V(v) = \begin{cases} 0, & 0 \le v \le v_{ci} \\ P_{rated} * \frac{(v - v_{ci})}{(v_r - v_{ci})}, & v_{ci} \le v \le v_r \\ P_{rated}, & v_r \le v < v_{co} \\ 0, & v_{co} \le v \end{cases} \tag{5.19}$$

This function is characterized by several different limits, which are the cut-in wind speed, the rated wind speed, and the cut-off wind speed. The first section of the function is for the wind speeds which are below the cut-in speed, essentially the speed for which the

DFIG is not turning quickly enough to sustain generation. The next section of the function is between the cut-in and rated speeds, which is the wind speed range over which the generator is able to produce power, but is not enough to reach the maximum potential of the generator. The profile of the power output of this region is modeled as a linear function over the range of the section's wind speed, starting at zero power output and ending at the turbine's rated power output. The actual output of wind turbines occurs more naturally as an exponential or power function, but the combination of the relatively small range and mild curve of the function means it is much more practical to evaluate this range as a linear function. The third range is the range between the rated speed of the wind turbine and the cut-off speed. At this speed, the power output of the turbine is constant, even as the wind varies, and this is therefore the most desirable range for the wind turbine to operate. The final piece of the function is the wind range beyond the cut-off speed of the turbine. The cut-off speed of the turbine is the wind speed at which the turbine disconnects its generator from the rotating shaft and essentially shuts down electrically for purposes of self-preservation. By using these zones, the output of the turbine can be interpreted from the wind data.

Thus, with the different formulas previously defined and the actual wind data collected, the probability analysis can be executed. The wind data are collected from the coastal regions of the Carolinas in United States, which provides a relatively steady source of wind when compared to other locations that are inland. The solar data from the same area was obtained by utilizing the National Solar Radiation Database, which records data regarding solar irradiance across the United States at participating weather stations, in this case an Air Force Base localized to the same area as the wind data. The final piece needed to determine the health of the system is the load profile, which in this case was provided for the distribution system of an electric utility within the same area as both the wind and solar resources. Additionally, the wind and solar data were compiled for the same calendar year (2009), as the same solar conditions that affect the wind generation will also affect solar output.

To reconstruct the normal distribution that is used for the first part of the statistical study, the parameters to be extracted from the solar data is the same as that for the wind speed, which are the mean and standard deviation. For the second probability function that is being investigated, The Rayleigh function, there is only one parameter that needs to be determined, and that is the parameter *b.* This can be determined from the mean of the data by using the following simple formula:

$$b = \frac{\mu}{\sqrt{\frac{\pi}{2}}} \tag{5.20}$$

Likewise, a temperature profile for the area, taken from the same Air Force Base, can be constructed to create the modification for the power output that was described previously. The final aspect of the parameters that must be determined is that of the load. The raw data, which is provided by a local utility, represents a distribution subsystem that contains a maximum of over 400 MW of load, with an average load of around 350 MW. As this is much larger, this is scaled to properly characterize the distribution subsystem. This took a small amount of processing, where the maximum and mean values of the real load were found in order to create a profile to use for the modeled distribution system. The mean value of the load was then used for the 6 MW point of the island. This gives a maximum island load of 7.2 MW, and a minimum of just at 3 MW. In this way, the distributed generation should still have the capacity of always meeting the load requirements, as long as there is a reasonable amount of the renewable resources present.

With the Weibull function established as a viable method for investigating the adequacy of the wind resource, a great range of analyses are then opened for exploration. The mathematical framework is straightforward, and also adaptable to the many different scenarios which wind profiles follow in nature. Lastly, the parameters and data for the analyses are laid out to provide a clear means of obtaining meaningful results.

5.4 Results of Probability Analysis

Mathematically, to determine the probability that the wind will occur between the value of nine and eleven m/s, the following formula is applied [30]:

$$P = F(b) - F(a) \tag{5.21}$$

Therefore, the estimated value of the wind speed at eleven m/s is 0.7, and at the wind speed of nine m/s is 0.4. Thus, the probability that the wind velocity will occur within this range is 0.3, or 30%.

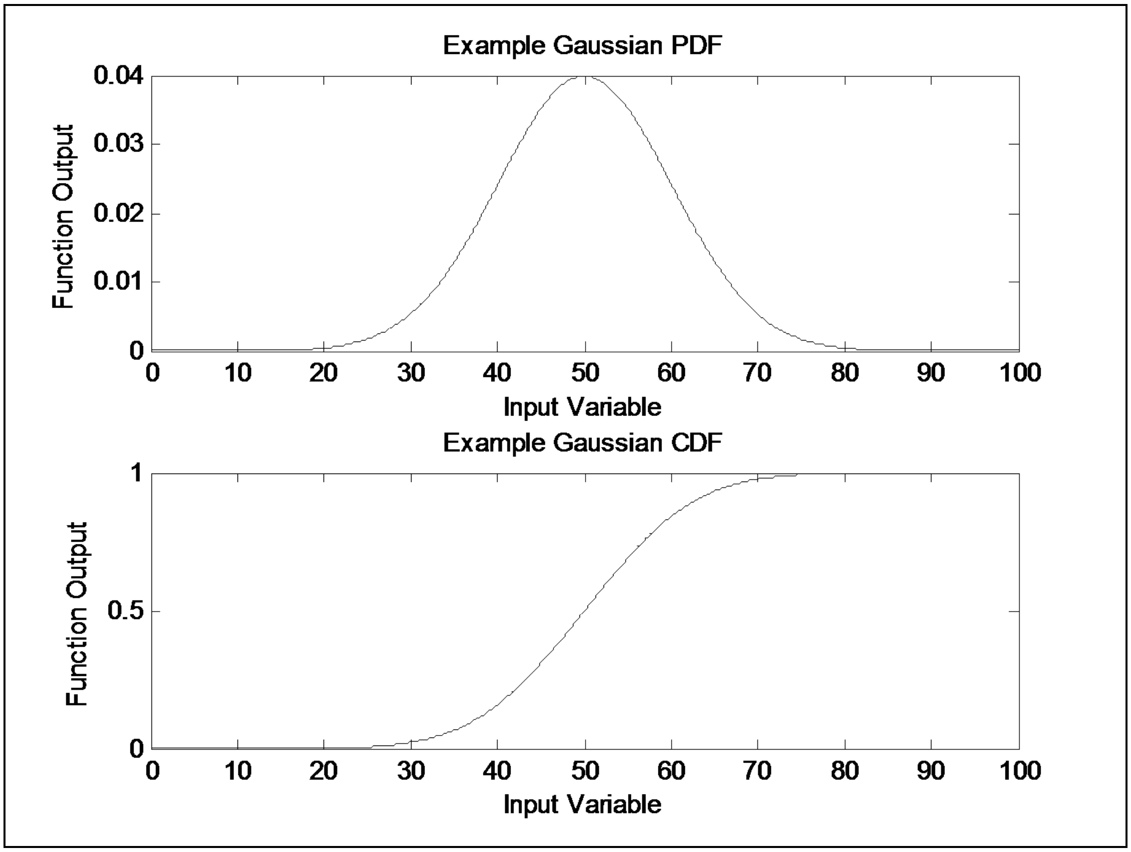

Figure 5.6: Typical Gaussian PDF and CDF

The most common way to represent a family of probability functions is to use the pdf instead of the cdf. The pdf is simply the mathematical derivative of the cumulative density function, and therefore has a total area of 1 for integration. This function helps to visualize the probability of the event more clearly and intuitively than the cdf. Using the previous example, the graph would show more of a bell curve that centers around ten m/s, and quickly approaches zero after the value of twenty m/s is reached on the abscissa. To determine the probability of the wind velocity occurring within a particular range, the following formula can be applied:

$$P(a < X \leq b) = \int_a^b f_X(x)dx \quad (5.22)$$

As for the contribution of the solar generation to the grid, it is relatively stable when modeled as consistent irradiance affected by randomized cloud cover. As it undergoes changes in generation it performs well without creating power swings in islanding generation due to its electronic control. Previously, solar generation was modeled utilizing the clearness index, a measure of atmospheric conditions such as cloud cover, to extrapolate a model of solar irradiance. However, this is not the most desirable approach primarily because the solar irradiance is constantly changing due to the sun's relative position in the sky. This means that the predominant factor in solar irradiance is ignored in the models. To gain a more accurate estimate of the solar generation, METSTAT was used to create a normal distribution modeling the solar output over a day with the effects of cloud cover. Examples of this can be seen in Table 5.1, where the different models of the solar irradiance are compared to the actual irradiance data. The cross-correlation returns the frequency with which the pdfs return a data profile that is consistent with the actual data used for the solar profile. As can be seen from Table 5.1, both functions correlate well with the available data, and both have a small edge for different seasons.

Table 5.1: Solar PDF Consistency

Season	Norm. Corr.	Rayl. Corr.
Spring	97.62%	95.31%
Summer	95.38%	92.21%
Fall	97.37%	97.57%
Winter	97.94%	98.2%

A beneficial takeaway from these results is that the normal distribution can be used to model the solar irradiance when direct solar data is available. This opens up the possibility for broad and innovative analysis of the solar resource, as the mean and standard deviation which define the function can be calculated and analysed by a broad range of software programs, or can even be calculated by hand. The performance of the solar profile as a normal function during the afternoon is displayed in Figure 5.7.

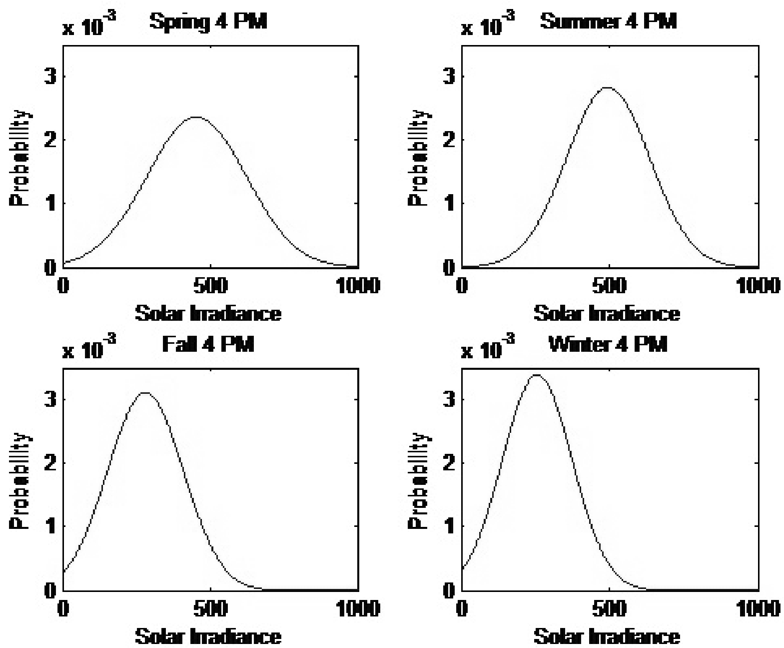

Figure 5.7: Simultaneous Plots of Solar Probability Functions

All of the seasons experience a fairly consistent profile, with a moderately sharp bell curve. Although it is lower during the fall and winter, it is still not highly variable. The benefit of this analysis shows that in comparison to wind, which has a fairly distributed range of wind speeds that may occur, the solar irradiance will stay more consistent. In practical terms, this means that it could be implemented with a higher degree of confidence in its output than that of a wind farm.

To begin the wind analysis results, a histogram of the wind data is compared to that predicted by the pdf as shown in Figure 5.8.

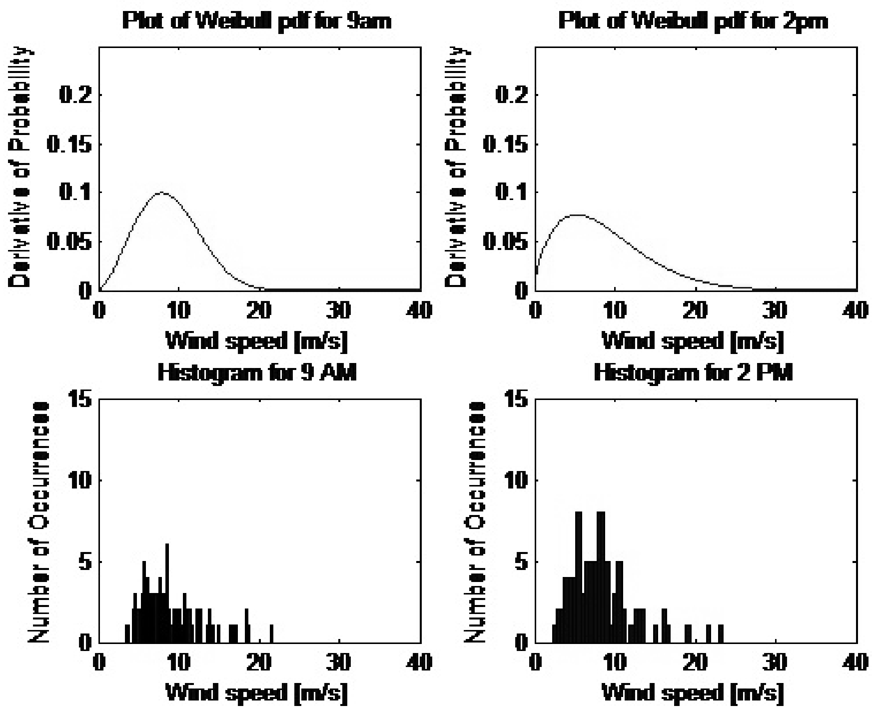

Figure 5.8: Contrast Between Best and Worst Weibull Correlation

The best and worst Weibull functions that correlate to actual wind probabilities for the winter season can be seen in Figure 5.8. The plot of the 9 AM hour appears quite similar to the histogram, whereas the histogram for 2 PM appears to be more Gaussian, as the Weibull takes on more of a Rayleigh form. To gain a better understanding of how accurate the Weibull pdf is in mimicking the probability of a potential output for the system, the cross-correlation of the data vector recorded for the wind speed and the actual data provide a glimpse as to the potential accuracy of the pdf. For instance, if the data vector is correlated against itself, the cross correlation is naturally 1, or 100%. If the Weibull pdf is correlated against itself, the cross-correlation yields a result of approximately 0.97, or 97%, because of the standard deviation and randomness associated with the function. Over an infinite number of samples from this cross-correlation, the result could be seen to approach that of 100% correlation.

Table 5.2: Correlation of Weibull Function

Hour	Spring	Summer	Fall	Winter
Midnight	0.9446	0.9858	0.9588	0.8883
2 AM	0.9483	0.9900	0.8542	0.9131
4 AM	0.9794	0.9886	0.7689	0.9081
6 AM	0.9816	0.9916	0.7501	0.8929
8 AM	0.9345	0.9918	0.7755	0.9548
10 AM	0.7866	0.9919	0.8440	0.9611
Noon	0.7768	0.9910	0.9301	0.9207
2 PM	0.8288	0.9912	0.9326	0.8708
4 PM	0.9197	0.9841	0.9584	0.8699
6 PM	0.9323	0.9860	0.9760	0.8931
8 PM	0.9609	0.9859	0.9853	0.9319
10 PM	0.9892	0.9839	0.9884	0.9212

Note how well the Weibull fits the wind data, in most cases exceeding over a 90% correlation. The cases where the correlation becomes lower are often the occasions where the function takes the form of a decreasing exponential, but the wind itself becomes slightly more like a uniform distribution. However, with an overall correlation of 91%, this still shows the validity of the Weibull model.

Now that the practicality of the wind being modeled by the Weibull pdf has been verified by the correlation of the pdfs to the actual data, the first thing to be noticed from the results are the consistent profiles generated by the wind. Normally, the wind profile that is generated by installing a wind farm inland generates a profile that appears much more like a declining exponential, as there is no steady wind production inland. However, in the case of coastal winds, the most distorted distribution profile the wind creates a Rayleigh-type function.

Table 5.3: Shape Factors for Different Times for Each Season

Season	**Noon**		**Midnight**	
	Shape Factor (k)	**Mean Wind Speed (m/s)**	**Shape Factor (k)**	**Mean Wind Speed (m/s)**
Spring	1.1065	7.5170	2.2658	7.9204
Summer	2.9045	5.3444	2.3525	7.2287
Fall	2.8883	7.5636	2.2682	7.0124
Winter	1.985	8.8745	1.8716	8.6641

The most exciting conclusion that can be drawn from this range of shape factors within the Weibull functions for the coastal region study is that much more wind is available to be utilized for the wind generation, and additionally, there is much less variance within the wind. This is beneficial for two reasons: first of all, with a base wind speed that is much closer to the cut-in speed of wind turbines, the utilization of wind turbine technology with lower cut-in speed mean that much more power could possibly be extracted from the wind than was previously thought to be possible. This returns higher utility factors for the turbines, making them more profitable for the utilities. The second reason that this is beneficial is the low variance within the wind speeds lead to generation that is much more consistent and reliable within the generation portfolio. This can be illustrated using the common scenario where most of the wind profile lies between

5 and 10 meters per second. Even though this is below the rated speed of the turbine, it is still extractable power that has a definite concentration. Contrast this to a theoretical land farm installation, which would have a distribution that is shaped like an exponential. This type of distribution could have more power that could be extracted within the rated range. However, no particular range of operation would have a high probability of occurrence, which would have the negative effects of reducing the ability to plan around the resource, and also having to have greater system flexibility to make up for the changes in generation.

Another topic of discussion in wind generation is when the resource will be available. In land-based installations, the daytime produces little wind, while the nighttime can produce significantly more. This presents the issue that the wind resource is classically poor during peak demand, and strong during off-peak demand. This, however, changes with location, and one way to roughly understand the amount of wind generation available in the coastal installation is to inspect the mean wind speeds at the different times of the day. The following table provides the mean wind speeds for every other hour for each of the days reconstructed for each season.

Table 5.4: Mean Wind Speeds Over a Day

Hour	Spring	Summer	Autumn	Winter
Midnight	7.9204	7.2287	7.0124	8.6641
2 AM	7.8003	7.0039	7.4360	8.6772
4 AM	7.6188	6.6678	7.8014	8.6987
6 AM	7.4710	6.2327	8.0301	8.7391
8 AM	7.4275	5.7438	8.0604	8.8012
10 AM	7.4604	5.3779	7.8975	8.8579
Noon	7.5170	5.3444	7.5636	8.8745
2 PM	7.5590	5.7684	7.1046	8.8282
4 PM	7.6046	6.4369	6.6620	8.7435
6 PM	7.6858	7.0522	6.4014	8.6568
8 PM	7.8157	7.3511	6.4415	8.5979
10 PM	7.9307	7.3725	6.7144	8.5708

What this table demonstrates, as seen in the summer season, is that the mean wind speed actually peaks in the evening sometime before midnight, and minimizes during the mid-day period. There are any number of reasons that this might occur, and one explanation is that as the sun sets, the land loses it natural warmth more quickly than the ocean, and therefore the air temperature then becomes imbalanced between the two areas. This leads to the movement of the air, until an equilibrium is reached sometime in the early hours of the morning. Note the consistency of the mean wind speed, which is a product of having an ideal location where the winds developed over the Atlantic Ocean naturally bank in the coast of South Carolina. To take the study to a deeper level, the expected MW level of the output of the turbines can be calculated using the pdfs, which differs from the simple information of mean wind speed.

Table 5.5: Typical MW Levels Over a Day

Hour	Spring	Summer	Autumn	Winter
Midnight	4.1532	3.2801	3.0297	4.4380
2 AM	3.6765	3.2714	3.7846	4.6233
4 AM	3.2011	3.4611	3.6962	4.3098
6 AM	2.9894	1.7995	4.5944	4.0598
8 AM	3.2051	1.3927	3.4923	5.2636
10 AM	3.4669	1.1680	3.7999	4.5110
Noon	3.5342	1.1813	3.6288	4.3787
2 PM	2.7013	1.6934	2.6863	4.9823
4 PM	3.5251	2.4065	2.6832	4.4853
6 PM	4.0301	2.8031	2.3094	3.9037
8 PM	3.8898	3.3673	2.2133	5.0389
10 PM	3.6066	3.5692	2.6327	4.2887

Since the mean wind speed can only provide a picture of how much wind is available for generation, using the pdfs and the knowledge of the range of the wind turbines, the probability of full power output and total wind power outputs can be ascertained for the different seasons. The power output was calculated above, and by adding the load along with the probability density functions this allows for the calculation of the probability of self-sufficient wind generation. This is reflected in the following table.

Table 5.6: Full Power Probabilities

Hour	Spring	Summer	Autumn	Winter
Midnight	52.1335	30.2586	36.9628	50.7013
2 AM	50.4626	27.7353	40.4571	52.4034
4 AM	46.9301	29.4965	41.1129	50.7551
6 AM	46.1912	23.7049	40.4648	51.1264
8 AM	36.6532	7.2286	38.8718	48.1692
10 AM	34.2760	3.1909	40.6123	48.7128
Noon	29.7186	0.4587	32.9069	50.8171
2 PM	32.6864	0.9037	26.5377	46.3056
4 PM	34.7715	3.4763	21.5889	40.9104
6 PM	35.6259	9.3295	20.1456	39.1358
8 PM	39.7780	16.5798	20.1767	40.8988
10 PM	41.4035	17.5841	22.8276	43.9731

This table reflects what was seen before generally by the table reflecting the mean wind speeds, as the possibility for full power output is generated over the different seasons. Notice that there are slight variations, as the shape of the Weibull function can impact the output of the wind. For instance, a sharply normal output with a mean at 8 m/s would produce very little full power output, whereas an exponential output decreasing from the origin with a mean at 8 m/s would potentially produce greater output.

After studying the wind probability density functions in such detail, it is important to note the limitations involved in such a study. The first limitation is obviously the discrepancy in the predictions from the probability density function from that of the actual data, as illustrated by the cross-correlation between the two. However, the histograms do illustrate an important point about the wind that supports using a probability density function as opposed to the actual data, which is the fact that using the actual data exclusively might lead to over-specification. Most of the histograms show a jagged profile, which are the result of having wind clustering. This can also be due to the relatively small sample sizes that are available for wind, so it stands to reason that a wind study over a period of a decade would be able to produce better results. The second limitation that becomes apparent when studying the wind profiles is the fact that although the probability density functions are useful in extracting total power outputs and odds of certain levels of generation, the use of the tool as a means of dispatching the generation may be dubious. The simple fact is that although the probability density function has roughly the same odds as producing a given wind output as the actual data, the probability that any of these two random data points are similar is quite low.

After the probability for both the solar and wind elements are found, it is then important to combine their results to find the health of the overall system. This is accomplished by using the wind results as a base, and then using the solar results as a modifier of this base system, as the wind has a far greater portion of the potential power generation. Thus, the probabilities of wind generation are divided into the categories of unhealthy, healthy, and self-sufficient. The solar generation, because of its size, is simply divided into the categories of unhealthy and healthy. To find the new unhealthy category of combined generation, the following formula may be applied:

$$H(Com) = H(W) + H(S) - [H(W) * H(S)] \quad (5.24)$$

This shows that the healthy combined probability can be found from the probability of healthy wind and solar (healthy in this case including the self-sufficient case). By subtracting this value, which contains the healthy and self-sufficient probabilities, the unhealthy value is found. The second modification is slightly more difficult, but operates in the same manner, as what is required is to find the window where healthy solar generation will boost the overall state into self-sufficiency. To find this for a typical load of 6 MW, at least 6 MW of renewable generation are needed for self-sufficiency. Therefore, the probability of wind producing between 5 and 6 MW combined with the probability of self-sufficiency is used for the probability outlined in equation (5.24) along with the probability of healthy solar generation. This gives the new combined value for system self-sufficiency, and this combined with the probability of the unhealthy state can be subtracted from 100% to then find the value of the system being in the strictly "healthy" category.

This can be most easily seen in an example, and a good example would be for the fall season at 2 PM, which has a good mix of both wind and solar generation. The following table details the probability associated with the individual resources and for the probability associated with the combination of the two.

Table 5.7: Example Combination of Renewable Probabilities

State	**Wind**	**Solar**	**Combination**
Unhealthy	23.2	80.4	18.7
Healthy	50.3	19.6	53.7
Self-sufficient	26.5	0.0	27.6

The most important result that could most likely be drawn from simply the probability analysis of the renewable resources is the expected adequacy of the resources, which is the probability that the combined resources will be able to meet the requirements for either the healthy or self-sufficient states. The following table lists those probabilities.

Table 5.8: Combined Probability of Healthy State

Hour	**Spring**	**Summer**	**Fall**	**Winter**
Midnight	0.765	0.729	0.703	0.751
2 AM	0.748	0.708	0.672	0.777
4 AM	0.745	0.679	0.625	0.792
6 AM	0.765	0.641	0.612	0.795
8 AM	0.729	0.598	0.663	0.822
10 AM	0.672	0.688	0.766	0.825
Noon	0.739	0.777	0.747	0.772
2 PM	0.772	0.833	0.836	0.751
4 PM	0.721	0.747	0.77	0.656
6 PM	0.704	0.745	0.648	0.635
8 PM	0.747	0.761	0.658	0.673
10 PM	0.792	0.752	0.693	0.723

5.5 Summary of Probability and Conclusion

Although the probability study of the renewable resources can be quite broad, the specific study of these resources specific to the situation of distributed generation and islanding allows the field to be narrowed. The solar probability study demonstrated that the formulas that have been classically utilized for analysis are unnecessarily complex. An easier set of equations can be developed through simpler formulas and still maintain a satisfactory degree of accuracy. For the wind analysis, it was demonstrated on several levels that the wind resource in this study becomes inadequate during daytime on-peak conditions, and increases during the night. Finally, it was demonstrated that combining the two resources can provide a complimentary action to improve the availability of renewable resources to a smoother profile over the course of the day. Next, this analysis can be combined with the transient analysis and operational scenarios to provide an overview of the operation of the system as a whole.

CHAPTER SIX

COMBINATION OF ANALYSES

6.1 Background of Combination of Analyses

So far, two distinctive types of analyses have been presented for the research, the first consisting of a transient time-frame system simulation, and the second of a year-long probability analysis of renewable resources. It seems that these are two completely disparate fields; however, if viewed correctly, they can be seen to be complementary studies that provide an overall view of the system. The questions that need to be answered then include the necessity of the combination of these studies, how such a combination could be executed, and how the earlier construct of operational scenarios helps to combine these studies.

Probability and transient analyses have been used as separate methods for studying generation, however for modern renewable technology it makes sense to begin combining such studies for several reasons. First of all, it serves to create a more complete picture of the generation situation created from the inclusion of renewable resources, as some research overlooks systemic difficulty in incorporating renewable resources, and system studies may not take into account the availability of the resources. Additionally, the level of generation available from the resources also dictates the effects on the system, therefore it follows that the two areas should be studied as complementary areas.

To combine these analyses, the method that will be used is based on using the operational scenarios discussed previously. These scenarios divide the potential states of the system into three different areas, which can each be characterized with a certain probability. By subdividing the operational scenarios into even stricter scenarios based upon generation levels and switching operations, a range of situations for which to obtain probabilities can be found and specifically simulated for. Thus, every major situation which may occur within the system can be simulated to find the system effects, and the probability of the situation can also be obtained. Thus, every situation can be simulated for both effects and probability, giving a more comprehensive analysis.

In exploring the possibilities associated with having a combination of these approaches, there are two different ways this will be utilized in the research. First of all, a retroactive analysis that strictly uses the data given to analyze the theoretical system for different trends will be presented, demonstrating its utility for comprehensive study. Then, a method for a predictive analysis will be presented along with some examples from the data sets.

6.2 Retroactive Analysis Using Combined Method

The retroactive analysis that can be drawn from these studies are a model of what a utility might do when investigating the integration of renewables into their generation portfolio. This starts by taking the historical data, completing a probability analysis with a given system to understand the different scenarios that may occur, and conducting simulations for these scenarios. The results that are generated by such a study can be of multiple forms, such as long-period and short-period studies.

When using the results of the probability analysis in combination with the scenarios for the health of the generation for the island, there is a broad diversity of information to attempt to understand. However, the most interesting scenarios are presented in Figures 6.1-6.4, which are a seasonal look at the results that can be obtained using this method (Figs. 6.1 and 6.2), a monthly interpretation of the generation mix (Fig. 6.3), and a daily progression that informs about the different states expected for July (Fig. 6.4). These results then what is meaningful about the self-sufficiency results obtained earlier, while also providing a full range of load profile against which to judge the adequacy of the renewable resources. What is also the core attempt of this progression of results is to show how different levels of operational time periods can be investigated.

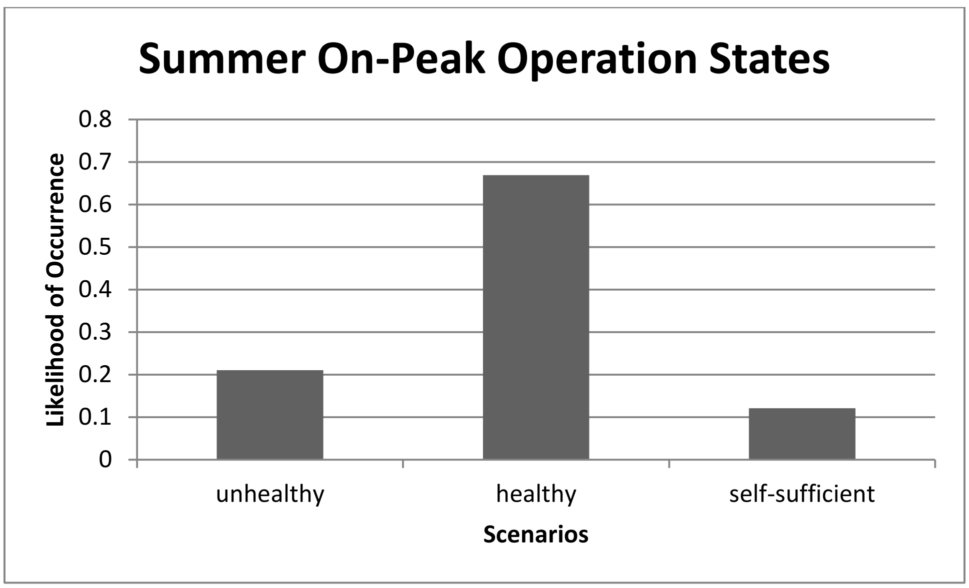

Fig. 6.1: Summer Peak Operating Scenarios

For the summer season in Figure 6.1, note how drastically the profile is dominated by the healthy state. This comes from the fact that some solar power is still available during this time period along with some wind, but that there is typically not enough to fully power the system. This would also be reflective of a wind profile from the pdf that has a more focused center below the level needed for self-sufficiency but still above the minimal amount needed to maintain the island.

- Note that 65% of the probability is for the healthy state, which denotes that this will have a consistently good mixture of renewable generation.
- The scenario could be further subdivided into the amounts of generation present, which will provide narrower parameters for simulation.
- From the simulation scenario with moderate wind and solar in a healthy state, the system displays good stability in handling the generation change, and the overvoltage due to the island switching is minimal, around 5%.

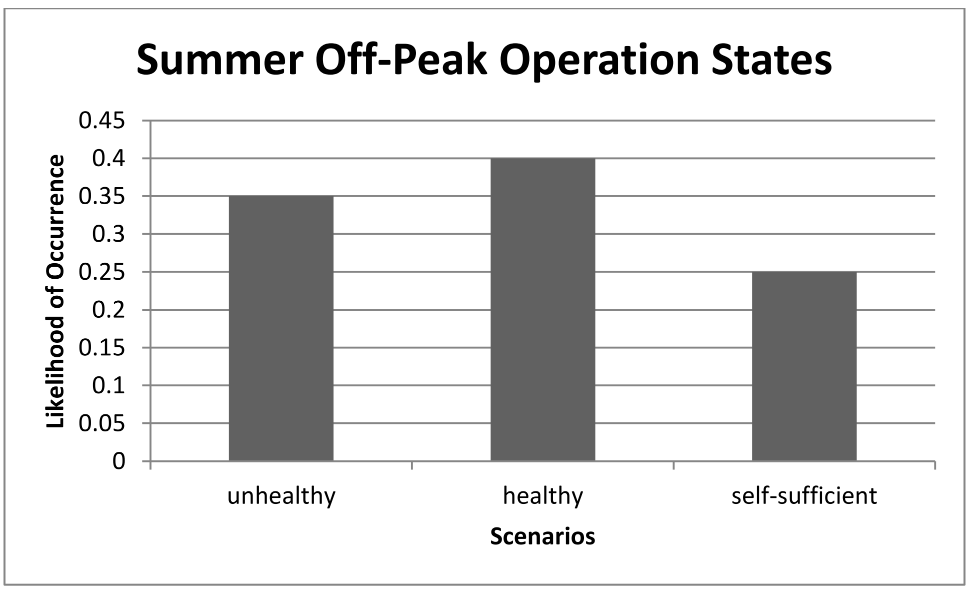

Fig. 6.2: Summer Off-Peak Operating Scenarios

The off-peak profile generated in Figure 6.2 demonstrates why the conventional understanding of wind changing its profile between the day and night is often true. While the mean wind speed at this time is not drastically lower than that of the summer, and both of the periods share a decent pdf profile, the generation here from the wind is able to meet the load without significant backup generation nearly 25% of the time. However, it is also completely inadequate nearly 35% of the time, which would indicate a shape of the pdf that is exponentially decreasing and has a great deal of variance.

- As there is no solar present for these scenarios, these situations can be narrowly defined as only containing wind power.
- In this case, each situation is roughly equally likely, and thus each scenario should be simulated for several different potential variations.
- For the unhealthy scenario, the system will experience voltage collapse, and the self-sufficient scenario shows a significant amount of generation drift as the wind turbines dominate the backup generation.

Thus Figures 6.1 and 6.2 show that for long-term planning, a profile of the adequacy of the different resources can be created for investigation, which can then be interpreted a number of different ways for scenarios and simulations. However, this shows a very broad, top-level view of the generation mix, and it is more desirable to know more specific mixes of renewable generation. This is presented in the next figure, where the specific generation mix is displayed for the period of a month (July) which can be used to define additional scenarios for simulation.

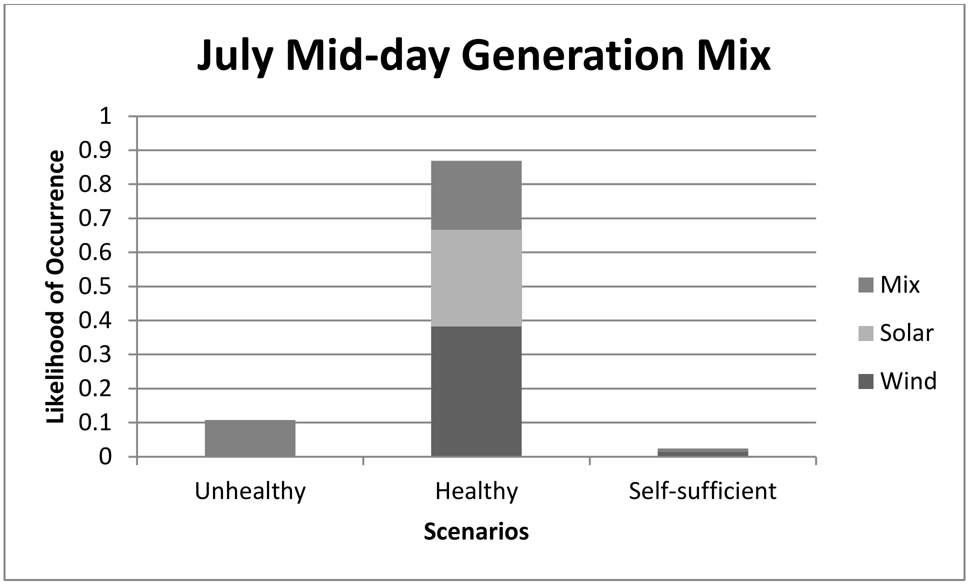

Fig. 6.3: Monthly Analysis of Generation Mix

Figure 6.3 shows a different take on the information that can be gleaned from this type of analysis, and in this case the summer was shortened to focus on the month of July, and particularly which resources make a contribution during the middle of the day (noon to 4:00 PM). Note in this case how the island is almost totally inadequate of being self-sustaining, which would be very useful to know for unit commitment for this period of the day. This interesting profile is created from the fact that although the wind is very inadequate during this part of the day when the air tends to be still, enough solar irradiance is present to ensure that the state rarely goes into an unhealthy situation. Also note from the graph how the solar by itself can be expected to be supportive of island health, instead of simply by mixing with wind, as is true for a very small percentage of the self-sufficient case.

- The self-sufficient and unhealthy scenarios combined have just over 10% of the share of potential generation, therefore the healthy scenario should receive the most analysis.
- Note how the solar generation could be considered the major contributor of generation, especially in light of most scenarios where wind dominates.
- With the solar only scenarios, the switching disruption, generation drift, and overvoltage are all greatly mitigated because of the mix of backup generation and electronically controlled solar generation.

The next figure breaks down the results into an even smaller time window, where the different scenarios are specified for the different load time blocks over the daily progression. This allows for the utility to see how the operational scenarios progress over time, leading to a greater comprehension of the availability of the resources as a whole.

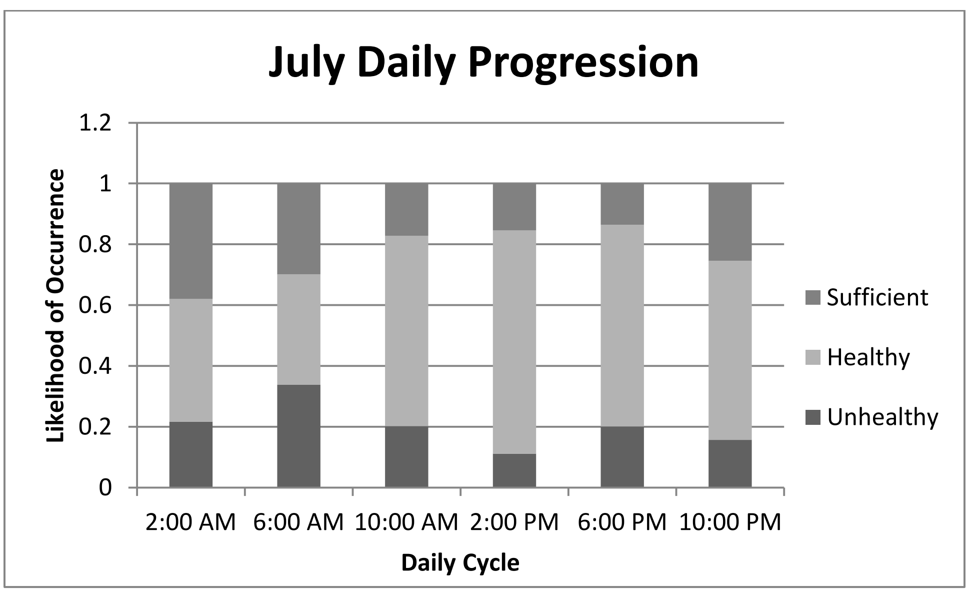

Fig. 6.4: Daily Progression of Operating Scenarios

In Figure 6.4, a daily progression of the availability of the resources is demonstrated, which could be useful for the daily operations of dispatching generation. Each column in this graph represents a different load level over the day, and the ability of the resources to meet that load. Note that for the middle of the day, the ability of the system to be healthy greatly increases in comparison to the other scenarios, and this is again reflective of the greater availability of the solar resource during these time periods. Conventional wisdom also holds that wind generation is greater at off-peak than at on-peak periods, and while this is greatly variable depending on area, the self-sufficiency of the island reflects that for this particular graph.

- For the greater part of the day, the healthy scenario is seen to be predominant.
- For the off-peak loading, the likelihood of being either unhealthy or self-sufficient are much more likely than the rest of the day.
- At 2:00 AM, a completely self-sufficient scenario in simulations is powered solely by wind, and this creates a large shift in current in the feeder when islanding, when it increases by over 50%.

From the above scenarios, it can be clearly seen that the probability aspect of the analysis provides a wide range of ways to analyze the system and the transient analysis can interpret the possibilities present in each scenario. Such an analysis of previous data is useful for understanding the potential effects of adding renewable generation to the system along with the true availability of the resources.

6.3 Predictive Analysis Using Combined Method

Attempting to predict renewable resource patterns has become the focus of great attention because of their increased incorporation into the grid. Probability analysis alone does not provide adequate means with which to address this issue, as it merely provides odds of an occurrence over an entire spectrum, instead of returning a singular result. However, by combining the analyses in the manner previously, the specific operational scenarios begin to provide a means for making some hourly predictions.

The basic methodology to making predictions using this analysis is to improve upon the popular current method of the static assumption of wind. Many wind farms are operated with the assumption that the next hour's wind speed will be roughly the same as the last, which works moderately well in areas that do not experience great variance in the wind. By using an approach incorporating the probability analysis, this can be made more accurate, and the operational scenarios provide concrete categories with which to return results. Mathematically, this is accomplished by taking the previous 4 hours of wind speeds, and making a simple prediction of the wind speed, which is then combined with the variance of the wind speeds over those hours to produce a Weibull function. This function can then give the probabilities of the different operational scenarios, which are the most important information to know regarding the island's relationship to the system. In the following figures, the described method is used to make predictions regarding an on-peak and an off-peak scenario.

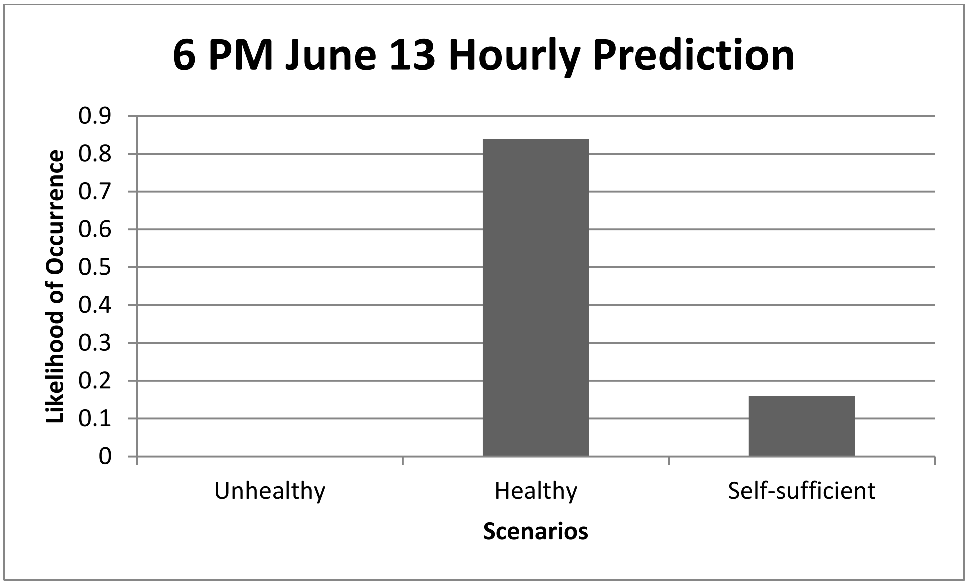

Fig. 6.5: Hourly Prediction for On-Peak Scenario

In Figure 6.5, the hours of 2-5 PM were used to make a simple prediction for the hour of 6 PM. Of note, for this case the predicted wind speed was 10.17 m/s with an actual hourly wind speed of 10.06 m/s; with a standard deviation of 0.88 m/s this was acceptable, and fell within the healthy scenario. While the method to create the prediction is not greatly important, and in fact the static model could be used to decent effect, what is more notable is the more definite nature of the results. In this case, there was essentially no chance for the system to become unhealthy based on the previous information, and also very little chance of it becoming self-sufficient. This could be very useful information for the hourly operations that are necessary for maintaining the grid.

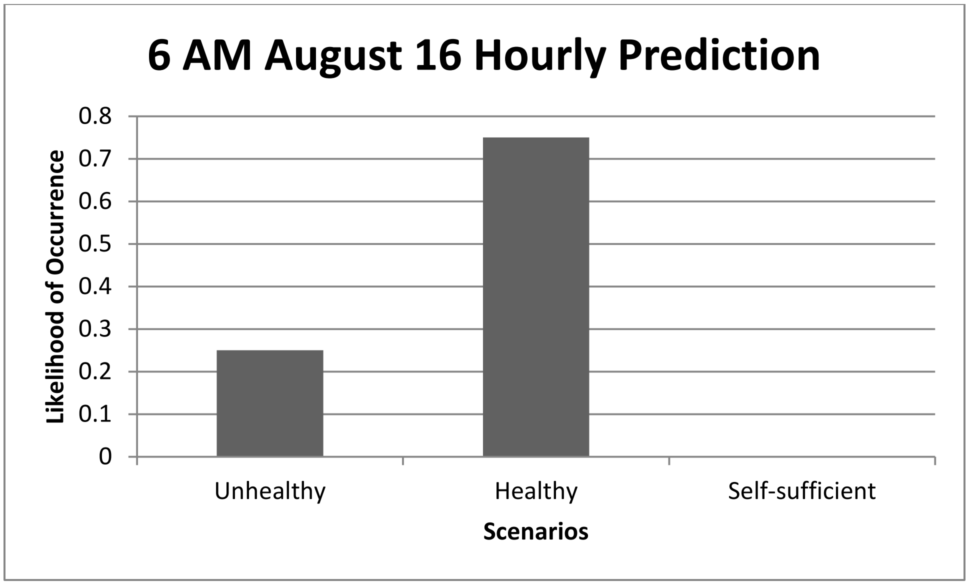

Fig. 6.6: Hourly Prediction for Off-Peak Scenario

Figure 6.6 is a complement to the previous figure, and again shows a situation where a particular scenario has been effectively eliminated. For this case the predicted wind speed was 5.45 m/s, and actual was 5.27 m/s, falling within the 0.73 m/s standard deviation expected and creating a healthy scenario. What is important to note for these two scenarios of Figures 6.6 and 6.7 is that both of the times were selected for analysis because the wind speeds varied a great deal in the period leading up to the prediction, creating more diversity in the results. For many hour predictions, virtually all of the probability falls within one category or another. Much as the retroactive analyses, these types of predictions can be increasingly narrowed, to find more constrained situations for which to simulate and find system behaviour.

By giving a possibility for the predictions of system states and operational parameters, the combined analyses provide a new measure of usefulness to operators that simple probability analysis may not have been able to provide before. Combined with the retroactive analysis, this provides a strong platform with which to begin analyzing renewables in distribution systems more comprehensively.

6.4 Summary of Combined Analyses

From the combination of the analyses, it was seen that a much broader view of the system can be obtained by using both the probability and transient analysis in correlation. A system-wide analysis can be carried out and broken down into increasingly smaller elements, which can provide a many avenues for gathering information on system operations. Taking this a step farther, it was shown that rudimentary predictive analyses could be improved upon and made reliable for hourly time periods, which could be of great use when renewable resources are incorporated into the distribution systems.

CHAPTER SEVEN

SUMMARY AND CONCLUSIONS

Throughout this research, broad areas have been tied together through the use of both probability analysis and transient analysis. A distribution system modeled in the PSCAD environment was used to analyze the effects of the inclusion of renewable generation in the distribution system with an islanding capability in a transient time frame. Additionally, the renewables were investigated utilizing real-world data for a probability analysis that complemented the transient study for the system.

In Chapter One, the background of the motivations for the study along with a literature review on the current state of research was presented. It was demonstrated that probability analysis had made great strides in the arena of investigating renewable resources, but that a transient study would also provide critical information as well. Typical areas of research were proposed to be expanded upon, including the creation of an islanding capability, and the use of a dynamic load profile. The outline of the rest of the research was then presented to provide a logical flow for the research to be presented.

In Chapter Two, the development of the system into a model that properly included both renewable distributed generation as well as an islanding capability was given. First, the basic parameters of the previously utilized model were detailed in preparation of the expansion into the additional features that the system would exhibit. Next, the location of the island was determined by analyzing the system, and placing it where it would be of greatest help to the system while still containing the renewable generation. The best placement was determined to be at the bottom of the shorter of the two feeders, where the islanding would promote system health and support as much load as possible. The next step was to determine the sizing of the renewable resources, and by using the size of commercially available turbines, utility factor, and average island load, it was determined that a nominal 12 MW of wind generation would be appropriate to install for the island, as well as 1.2 MW of solar generation.

In Chapter Three, the important differences between previous studies and the current study in the area of system load was detailed. To begin, the issues with assuming a static load for previous studies was addressed, along with the potential solutions that this study intended to present. The first part of the solution was to introduce a dynamic load profile to the study for each season with an overall average of approximately 6 MW, which can provide a much clearer picture of the true adequacy of renewable resources. Next, the systemic idealization of loads as being balanced was addressed by unbalancing all of the loads within the system while simultaneously rotating the phases of unbalance, and recording all of the adjusted values. Finally, alternatives in the solutions of the load such as an attempted harmonic experiment were introduced, and reasons for their ultimate discontinuation were provided, namely the lack of effect on the system.

In Chapter Four, the transient analysis of the system was presented as one of the major cornerstones of the research. One program that is capable of carrying out this type of simulation is PSCAD, which allows for a wide variety of electrical power systems to be modeled and simulated for both transient and steady-state time frames. All that had to be done was properly tailor the system for being run in the PSCAD environment. From these simulations, it was seen that the effects of islanding with distributed generation created similar effects to some types of disturbances but not on the scale of warranting concern for the system, apart from the voltage rise experienced by the island loads.

In Chapter Five, the probabilistic aspect of the study was presented from its mathematical foundations to its practical implementation in the Carolinas to finally a sampling of the wide array of results obtained. The first aspect addressed was that of the solar probability, which in previous studies appeared to be overly complex, therefore alternative solutions were proposed for this research. In the next part, the background of the wind analysis was presented along with the parameters of the research of the renewable resources. The results of several aspects of the study were then presented, highlighting the ability of the simpler methods to model the solar irradiance, and the confirmation of the distinctive pattern of wind generation to peak at night and lull in the day.

In Chapter Six, the summation of the research was presented as the combination of both the transient analysis and the probabilistic analysis. First, a background of the analyses and how they could be feasibly combined into a single study was presented. Next, a study that would mimic a system study of retroactive analysis was conducted from the viewpoint of a system adding renewable resources in the form of distributed generation with islanding capability. Finally, a method for creating a predictive analysis was given, along with results which displayed the accuracy of the method for hourly predictions.

Several conclusions have been drawn through the execution of this research from each area of analysis. From the probability analysis, it was shown that for at least the region in question, wind generation becomes inadequate over the daytime peak hours, and increases to it greatest generation potential during the night. Also, it was demonstrated that the complex mathematical techniques used for the calculation of solar probability is unnecessary for many applications, as simpler functions can fit the profile of solar generation reasonably well. From the transient analysis, it was seen that the inclusion of an islanding capability within the distribution system does not necessarily worsen the transient effects expected from events such as faults and generation switching. From the viewpoint of utilities and system operators, the most significant effect found was the increase in bus voltage in the island when disconnected from the grid, which could require additional measures to prevent it from becoming an issue. In the combination of the analyses, multiple methods for utilizing the data to create more comprehensive views of the system were demonstrated, signifying the potential uses of such a combination. Lastly, a simple method for creating predictive analyses for system operators on an hourly basis was given, which could be of great use with the expanding inclusion of renewables in the distribution system.

APPENDICES

Appendix A

Distribution System

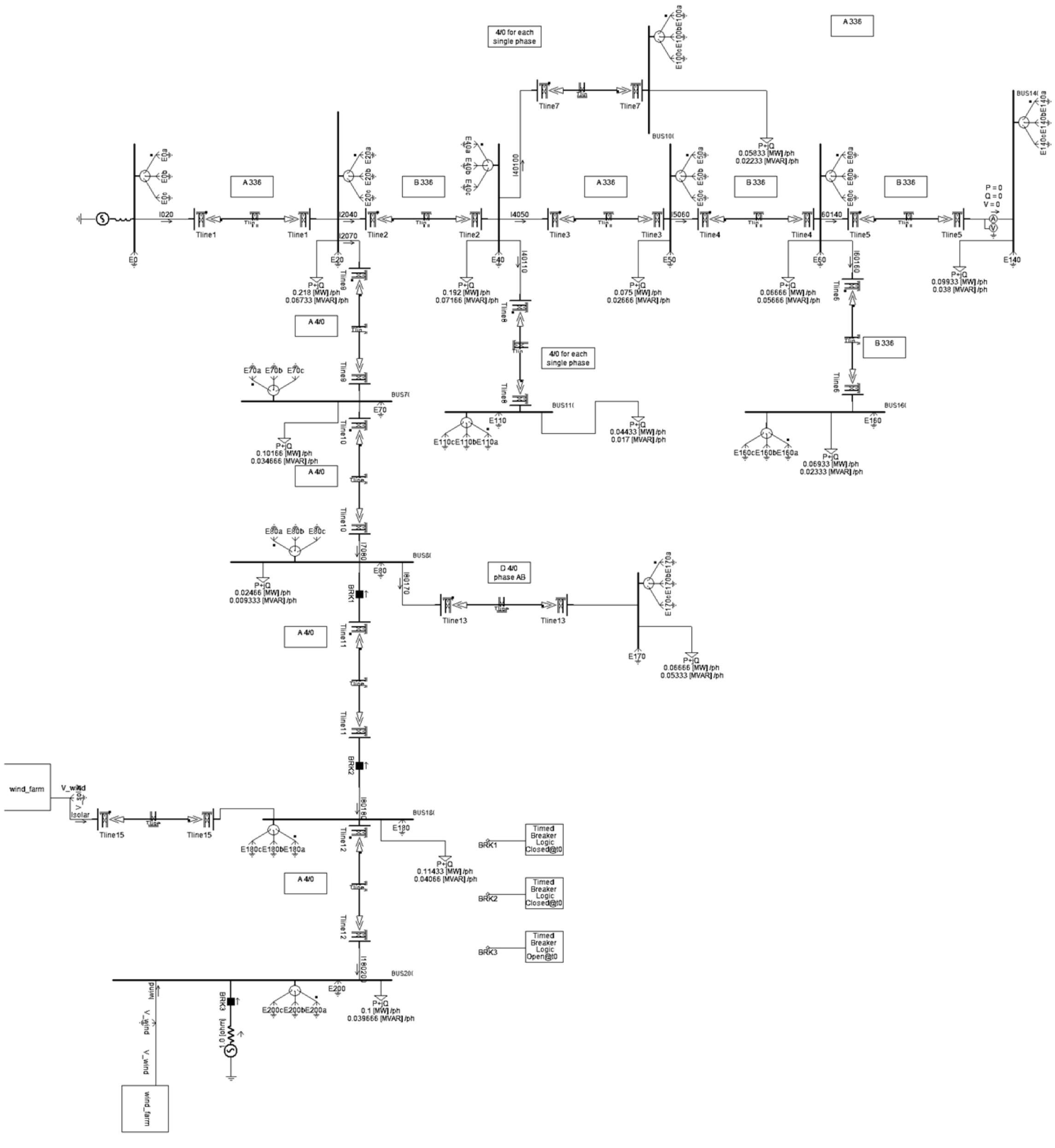

Figure A-1: Modeled Distribution System

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